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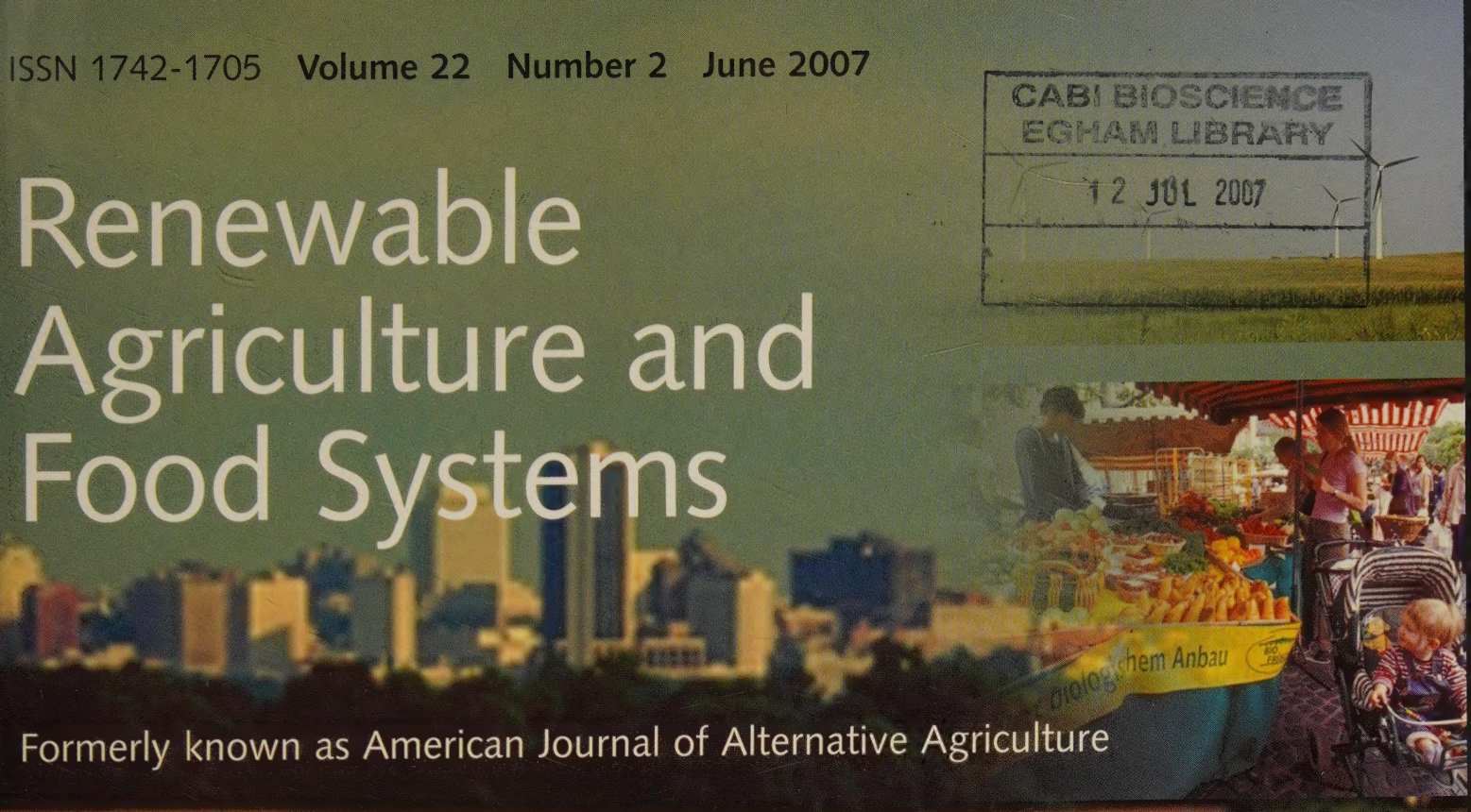

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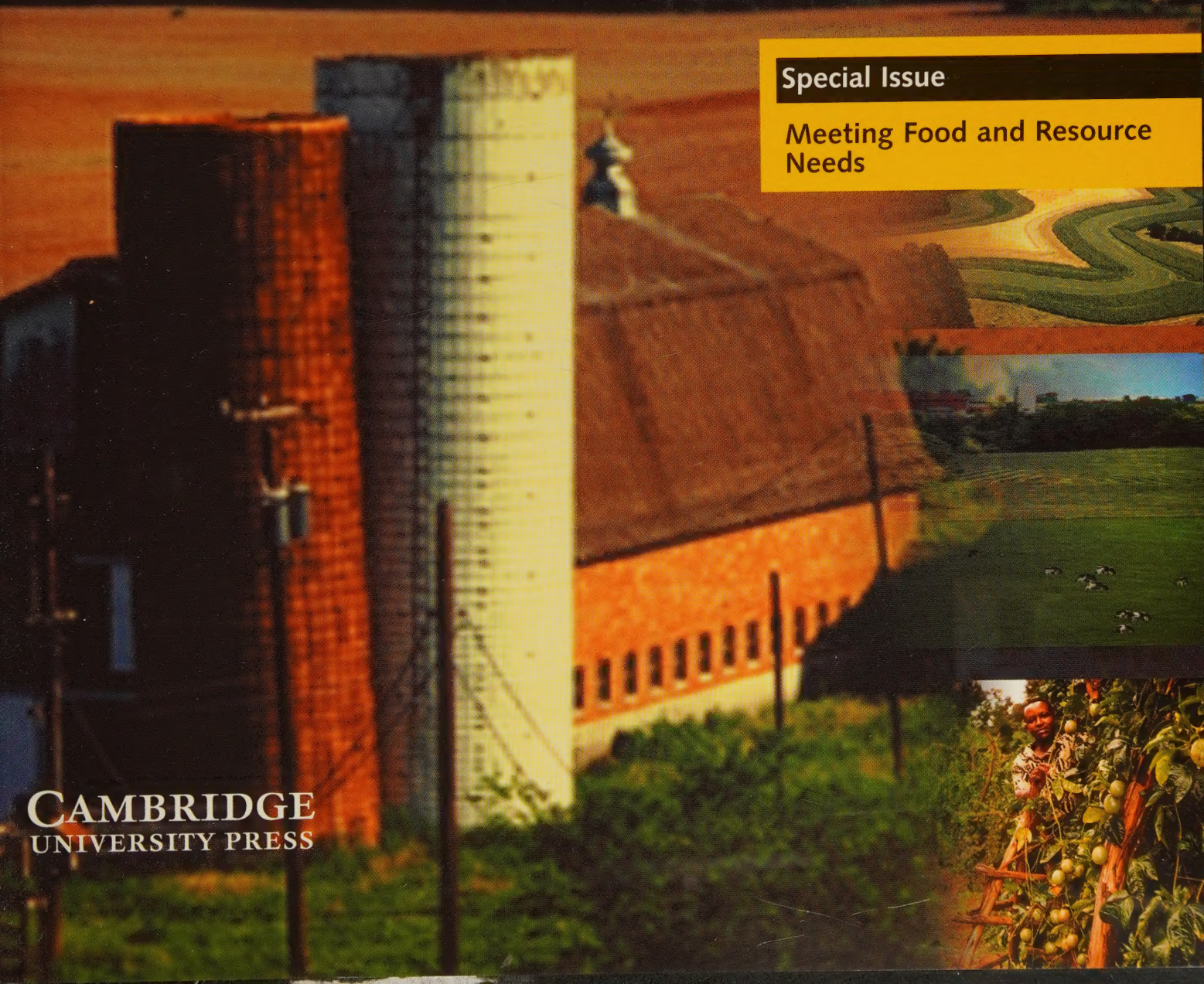

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Editor-in-Chief
John W. Doran, USDA–ARS, 116 Keim Hall, University of Nebraska, Lincoln, NE 68583-0934, USA
Email: rafjournal@cambridge.org

Forum and Resources Review Editors
Fred Kirschenmann, Leopold Ctr. For Sustainable Ag., Iowa State University, Ames, USA.
Email: leopold1@iastate.edu
Mark Liebig, USDA-ARS, Mandan, ND, North Dakota, USA.
Email: mark.liebig@ars.usda.gov

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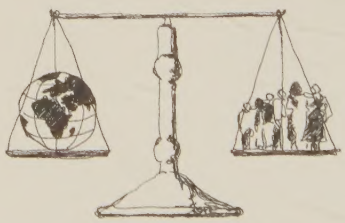

"Sustaining Earth and its People"

Scales image: Design, George Eisele, Lincoln, NE; artwork, Pat Scullion, ASA/CSSA/SSSA, Madison, WI, USA
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Editorial: Balancing food, environmental and resource needs

Global agriculture has faced unprecedented changes over the past 50 years. Initially, the needs of a world population that had doubled to over 6 billion were met by two to threefold increases in global food production through 'green revolution' agriculture, development of high yielding plant varieties, improved irrigation and crop management practices, and increased use of fossil-fuel based fertilizers and pesticides. Although food availability is no longer a problem in industrialized countries, food insecurity and persistent poverty still plagues one-half of Earth's people.

Recent United Nations reports estimate that some 840 million people on Earth are hungry and close to 3 billion live on less than the equivalent of $2 (2 Euro) a day[1,2,3]. The 2002 (1996) World Food Summit goal of halving the world's hungry by 2015 seems unlikely without a change in current food production and distribution systems[4]. Aside from meeting the continued requirement for increased food production, agriculture is now challenged: to improve health and social well being of people (better nutrition for the poor and balanced nutrition for the rich), reduce dependence on fossil fuels, adapt to climate change and extreme weather, reduce environmental degradation and decline in the quality of soil, water, air and land resources all while relying on fewer farmers (<1% of the population in USA) in increasingly urbanized societies throughout the world. These more recent challenges have led increasing numbers of people to realize that our current systems of agricultural production are not working as effectively as they have in the past. We need an agricultural paradigm that relies more on biology, ecology and sociology, than on the primarily one-dimensional physical and chemical management approaches of the past. Agriculture systems are needed which utilize food production and distribution systems that rely less on non-renewable, petrochemical resources, and more on renewable resources from the sun for food, feed, fiber and energy. We must meet global food needs based on the soil, water, land, and fertility resources that are readily available at present without compromising the capacity of future generations in meeting their food, environmental, and resource needs. Whether these needs can be met by 'organic' agriculture is unknown and is the lively topic of debate in the Forum discussion on 'Can Organic Agriculture Feed the World' of this special issue of *Renewable Agriculture and Food Systems* (RAFS) on 'Meeting Food and Resource Needs'.

In response to the Forum discussion, Dr Fred Magdoff, author of the paper on 'Ecological Agriculture' in this issue of RAFS, notes that comparatively little organic systems research has been done and the best ways to customize organic production practices are not really known yet. Scientifically, this research is still in its infancy. 'In fact, some of the "organic systems" that I've seen in experiments were not all that customized to the individual site, not run by organic farmers, but rather just using a standard combination of "organic" practices'. Taking an ecological approach may or may not be organic, although most approach organic by taking a preventive (problem prevention) approach to soil, crop, and animal management. As pointed out by Magdoff the key issue is that through our understanding of basic ecological principles, practices can be developed to provide high productivity, have minimal adverse environmental effects, and eliminate or decrease most pest problems. In the developing world (especially Africa), where nitrogen fertilizers are VERY expensive, the use of legumes, animal manures, leaves, etc. to help 'prevent' or lessen nitrogen deficiency is a very important issue—organic or not!!!! The use of local nutrient sources also provides organic matter to the soils, thus improving their biological and physical properties as well as chemical properties. It is easier to have an ecologically sound system when it is based on mixed crop and animal systems. Animal/crop systems provide many advantages over monoculture crop systems. For example, when ruminants are part of the system there is a direct economic use for a legume cover or forage crop, while still getting the nitrogen advantage of the legume, but some comes via the manure instead of directly from the plant. The real issue is to do the best job one can in managing above and below ground habitats to maximize the chances of getting healthy crops and minimize the chances that pests will be a major issue (by stressing pests and enhancing beneficial species). As pointed out in the Forum article by Badgley and Perfecto, the Cuban Food System was able to maintain a sustainable food system based on agroecological principles when large-scale use of fertilizers and pesticides was no longer possible after 1990.

Fred Kirschenmann, Resources Review Editor for RAFS, notes that any discussion on 'feeding the world' should include the new circumstances in which that feeding is done—namely, the end of cheap energy, more unstable climates (due to climate change), and much less available water. It is now generally conceded that we have either reached peak oil or will reach it by 2010, that climate change is already here for farmers, and numerous studies have pointed out that we are drawing down our ground water due to agricultural irrigation at rates that are not sustainable—especially in China and India where 60–70% of grain production is dependent on irrigation. Research in

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the Philippines has indicated that rice yields are already adversely affected because of higher night temperatures causing greater night-time respiration. These new realities will especially impact high-input monocultures since they depend on fossil fuel inputs for fertilizer, pesticides, and irrigation, and since highly specialized monocultures require relatively stable climates—when you have 92% of cultivated acres in corn and soybeans, as we do in Iowa (USA), then you need a climate that is consistently favorable to those two crops—which we are not likely to have in our new climate future. It is also questionable whether we can maintain our highly centralized global food system, with food traveling thousands of miles from field to table, in our new energy future; our future food system will have to be decentralized. Anyone thinking that we will be able to make an easy transition from our fossil fuel dependent era to an era of renewable energy is simply not paying attention to the energy efficiency ratios. For all of the industrial era we have been relying on cheap 'stored' energy which has accumulated in the earth over millions of years. We have now essentially tapped out that resource and will have to learn to live with 'current' energy and none of it will be as cheap as stored fossil fuel energy. So farming systems based on biological synergies, rather than energy inputs, will have the comparative advantage in our new future[5]. So, well-managed, ecologically based organic farms may have an advantage in our new world over the much more energy intensive conventional systems, but, whether we will be able to feed a world of 10 billion people with either system in our new energy/climate/water future cannot be predicted with any certainty.

This special issue of RAFS on 'Meeting Food and Resource Needs' has furthered the Journal's goal in providing a forum where conventional agriculturalists, striving toward more sustainable systems can interact with others in organic, biological, and biointensive agriculture to develop an agriculture that will achieve the vision of 'Sustaining Earth and Its People'. In addition to the Forum discussion and individual papers on 'Organic Agriculture and the Global Food Supply', and 'Ecological Agriculture' several others deserve mention. Glenna and Jussame, presenting the similarity of interests of organic and conventional farmers for commitment to self-seeking economic interests but differences on use of GM crops, marketing and environmental values and practices, suggested validity of portraying organic agriculture as an alternative vision to industrial agriculture. In a survey to define barriers to the adoption of Integrated Pest Management (IPM) by commercial cranberry growers in the USA, Blake et al. found that highly experienced full-time growers frequently use more IPM practises and, although many growers had the perception that IPM can pose measurable economic risk, over 90% of respondents agreed that IPM can reduce pesticide levels in food and the environment, and can help preserve beneficial insects. Mburu et al. assessed the feasibility of mechanical mulching technology as a higher yielding, more intensive alternative to slash-and-burn farming in the Amazon, and found a low acceptability among farmers due to higher inputs of labor and inorganic fertilizers and the need for two cycles of profitable crops such as cassava and beans. Peters et al. present a fascinating model assessing how human patterns of meat and fat consumption dramatically influence agricultural carrying capacity and land resource use in New York State.

Ultimate success in alleviating hunger, malnutrition, poverty, and soil, environmental, land and people resource degradation globally in the technically complex world of the 21st century, however, will not come solely from intensive input or organic agriculture alone but rather a hybridization of both approaches. In addition, we have learned that sufficient food production is no guarantee that the massive numbers of poor people will be able to eat an adequate diet. Thus, access to adequate supplies of food must be viewed as a human right and, as long as poverty persists, governments must make special efforts to ensure that access. A focus on existing conventional and emerging organic systems limits the possibilities. Instead, the emphasis should be on developing cropping systems that best contribute to a set of well-defined performance parameters that ensure adequate food supply, farm family income, treats farm labor well and farm animals humanely, and protects environmental quality and natural resources. If a system meets these criteria, it should not matter if it complies with rules prescribed for organic production systems, or any other rigid set of prescriptions for crop and soil management.

A final note, in his 2006 address to the World Congress of Soil Science in Philadelphia, Jeffery Sachs, author of *The End of Poverty* (see book review in this issue), Director of the Earth Institute at Columbia, and special advisor to the UN Millennium Goals Task Force, identified the central role of soils and soil fertility as a key step in unlocking poverty and soil degradation in Africa[6]. He reaffirmed needs identified by Soil Scientists Pedro Sanchez and Cheryl Palm in the Millennium Villages Project to increase the nitrogen and phosphorus supplying power of soils through use of commercial and organic fertilizers and nitrogen fixing trees/alley crops to increase potential crop yields to farmers by three- to tenfold. Sanchez called for another 'green' revolution in Africa, one that would rely more on biological processes and enhance, rather than degrade, soil and environmental quality. In further discussions, and in Magdoff's article in this issue, we envision a need for a 'triage' approach, using nitrogen and phosphorus (purchased or donated) as needed to initially reclaim the yield-producing potential of many degraded African soils. However, a rapid transition to approaches such as Biologically Intensive Agriculture is needed to sustain productivity, reduce soil degradation, and shift reliance to mainly local resources for food production and land sustainability for present and future generations.

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John W. Doran
Editor-in-Chief

Fred Kirschenmann
Resources Review Editor

Frederick Magdoff
Contributing Author

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Preface

Renewable Agriculture and Food Systems is a multi-disciplinary journal which focuses on the science that underpins economically environmentally and socially sustainable approaches to agriculture and food production. The journal publishes original research and review articles on the economic, ecological and environmental impacts of agriculture; the effective use of renewable resources and biodiversity in agro-ecosystems; and the technological and sociological implications of sustainable food systems.

It also contains an open discussion Forum, which presents lively discussions on new and provocative topics. However, the opinions of the Forum and responses are solely those of the authors and do not necessarily reflect the opinions of *Renewable Agriculture and Food Systems* or Cambridge University Press.

John W. Doran
Editor-in-Chief, *RAFS*

Can organic agriculture feed the world?

Catherine Badgley and Ivette Perfecto

Forum

The prospect that organic agriculture has the potential to feed the world is welcome news in light of the contradictions of modern agriculture[1]. These include the massive productivity of green-revolution agriculture yet the stubborn persistence of hunger and malnutrition, the loss of small farms even though they are more productive and contribute more to local economies than do large farms[2], and the pervasive environmental destruction by agricultural biocides and synthetic fertilizers even as more and more ecological services of agricultural landscapes are being recognized[3]. Organic agriculture *per se* cannot resolve all of these contradictions, but its potential to provide enough food to feed the entire world opens the door to the creation of a new kind of food system based on agroecological production principles. We (Badgley et al. in this issue) have demonstrated two critical points. The first is that the relative yields of organic versus non-organic methods (green-revolution methods in the developed world, low-intensive methods in the developing world) suffice to provide enough calories to support the whole human population eating as it does today. This conclusion is based on a global dataset of 293 yield ratios for plant and animal production. The second point concerns nitrogen fertility. Data from 77 published studies suggest that nitrogen-fixing legumes used as green manures can provide enough biologically fixed nitrogen to replace the entire amount of synthetic nitrogen fertilizer currently in use. Thus, the principal arguments from critics of organic agriculture are invalid. These results are controversial, partly from prejudice and vested interests in the current agricultural system and partly from disputed aspects of the analysis. While this study claims that organic yields and nitrogen fertility methods *could* feed the world, it does not forecast yields for any particular crop or region, nor does it claim that a global organic food system would necessarily increase food security anywhere. Food security depends on policies and prices as much as on yields.

Our study is not the only one to reach this conclusion. In 1990, Stanhill[4] came to a similar conclusion about organic production based on a compilation of data from North America and Europe (his average yield ratio was the same as ours for the developed world). More recently, Halberg et al.[5] modeled scenarios of conversion to organic agriculture in Europe, North America and sub-Saharan Africa, using a globalized market model. They concluded that large-scale conversion to organic agriculture would not severely diminish either the global food supply or food security in developing regions. They noted that food policies favoring local food availability, rather than export crops, would enhance the impact of conversion to organic farming and increase food security in sub-Saharan Africa.

Reviewers raised issues that merit dialogue beyond the context of the article. The first issue concerns the differences in crop-rotation patterns between organic and conventional grain agriculture. The second concerns the reliability of different kinds of sources (i.e. peer-reviewed versus gray literature) for agronomic data.

Rotation effect. Organic grain production frequently uses a different rotation cycle than conventional production. This difference complicates the comparison of yields

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between organic and conventional systems without some kind of time adjustment for grain that must be grown in a longer rotation cycle by organic methods. Corn, wheat and rice, the world's staple grains, are grown in approximately equal quantities (in megagrams) on a global basis[6,7]. In the US, corn and wheat are usually grown in rotation[8]. Corn is typically grown in a longer rotation under organic than conventional methods. For wheat, it is not clear that organic and conventional rotations differ in length. Most rice is grown in irrigated fields so tailored to rice production that other plant crops are not usually included (although green manures and animals can be included); organic and conventional methods for rice do not require different rotations.

Thus, corn is the main crop for which the rotation effect is an issue. A survey of corn/other crop rotations from the sources of yield data cited in Badgley et al.[1] (this issue) reveals that conventional corn was grown 25–60% of the time in rotations of 2–6 years, and organic corn was grown 25–50% of the time in rotations of 2–4 years. For the sake of a quantitative example, we can determine the yield adjustment for two widely used rotations of corn—a 2-year rotation of corn–soybeans under conventional management and a 3-year rotation of corn–soybeans–wheat + cover crop under organic management. All other things being equal, the organic system would produce only 67% as much corn as the 2-year conventional system would. If we multiply all of the individual yield ratios for corn in our dataset for the developed world by 0.67 and then recalculate the average yield ratio for grains, the result is 0.84 instead of 0.93. The reduction in caloric output from the lower average yield ratio for grains in the developed world results in a change from 2641 to 2523 total kcal person^{-1}day^{-1} in Model 1 (based on yield ratios from developed countries) and from 4381 to 4358 total kcal person^{-1}day^{-1} in Model 2 (based on yield ratios from developed and developing countries). Even with this time-adjusted correction for corn, both models generate enough calories (i.e. >2500 kcal person^{-1}day^{-1}) to feed the current population. These calculations are conservative since many conventional rotations feature corn less than 50% of the time. Organic rotations are capable of sustained production of grains rotated with other crops, as demonstrated by the Rodale Farm Systems Trial[9]. A more thorough evaluation of rotation effects requires quantitative comparison of the plot-to-plot yield differences between organic and conventional production and the rate of change in both organic and conventional production methods as a function of the rotation sequence.

Thus, the necessity for different rotation schedules would decrease the production of corn. But since overproduction of corn has depressed the price of corn for many years, this change could actually benefit farmers economically.

Gray literature. A reviewer raised the concern that our quantitative results were suspect because a number of our yield ratios come from the gray literature. Actually, 74% of the studies included in our analysis are from peer-reviewed journals. For a study of this sort, which makes a global-scale analysis, it is important to include as many studies as possible from as many regions as possible. We included studies of three kinds: controlled experiments of two or more management methods, paired-farm comparisons in regions with the same soils and climate and comparisons on the same farm before and after a change in management practices. All three kinds of studies could be found in both peer-reviewed and gray-literature sources. It is worth noting that some gray-literature sources are quite reliable, such as the technical reports of respected agricultural experiment stations (the Henry Wallace Experiment Station, Maryland; Kellogg Biological Station's Long-Term Ecological Research Site, Michigan; the Organic Farming Research Foundation, California). Three published works that we consulted for data also cited a mixture of peer-reviewed publications, gray literature and personal communications. Stanhill's[4] compilation is largely supportive of organic farming, while McDonald et al.[10] (which focuses just on the system of rice intensification) was skeptical. The third source was the book by Lampkin and Padel[11], which cites a similar range of sources for yield information. The point is that our compilation is not unusual in the kinds of sources used for analysis.

The most problematic source from the reviewer's standpoint was the report by Pretty and Hine[12] based on survey data from 52 developing countries. Yields were compared before and after farmers adopted specific agroecological practices. An analysis based on data from this report was subsequently published in *Agriculture, Ecosystems and Environment*[13]. The main reason for including many of the quantitative comparisons in this report is that relatively few published studies are available from farms in the developing world. In order to evaluate whether the survey data biased our results for the developing world, we performed a significance test on the survey data compared to data from experiments and paired farms. The test failed to reject the null hypothesis that the means in yield ratios do not differ significantly. (This test is explained in detail in Appendix 1 of Badgley et al.[1].) We concluded that the use of survey data from the report of Pretty and Hine[12] did not unduly bias our results for the developing world. We note, however, the need for more quantitative, experimental comparisons in developing countries.

One controversial management practice is the system of rice intensification (SRI) in developing countries. Its proponents claim that it boosts yields substantially, while its critics argue that best-management conventional practices perform just as well. A reviewer commented that our cited publications on SRI did not provide the minimum information about soil and environmental conditions for the sites where the studies were performed. This criticism applied to some of the studies cited on both sides of the debate. We tried to avoid bias by using data from both

proponents and critics in the debate. Furthermore, global estimates by definition involve generalities. Detailed information about soils, climatic conditions and specific management practices was not given for all the studies, regardless of publication source. In principle, these unmeasured variables would favor yields in the conventional system in some instances, while in others they would favor the organic system. There is no reason to think that the lack of information about these variables would bias our study in any particular direction.

In general, we recognize that the high yield ratios from developing countries likely result from the fact that many existing farming practices do not involve optimal amounts of synthetic fertilizer, and may not be managed optimally in numerous other ways. The adoption of organic methods in these settings is a huge improvement. However, our aim is not to demonstrate the superiority of organic farming over conventional agriculture. Our aim is simply to investigate whether organic agriculture can produce *enough* food to feed the world's population—ours is a sufficiency argument. It is appropriate to use yields from suboptimal existing systems in developing countries, because these systems are representative of much of the developing world and most of the world's farmers.

Going forward. Readers of this journal are well aware of the achievements of alternative agricultural systems both agronomically and economically. These achievements would multiply with additional research on locally suitable cropping systems, fertility methods and pest management for different agricultural regions. Changes in agricultural policy are essential and could foster changes in farming and marketing practices within a few years. As an example, the Cuban food system underwent massive reorganization of farming and marketing methods after the fall of the Soviet Union in 1990[14]. After a few years of crisis, exacerbated by the US economic blockade, Cuba now has one of the most progressive food systems in the world. A global food system based on agroecological principles *is* possible and there are urgent reasons to move in this direction.

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Catherine Badgley is a research scientist with the Department of Geological Sciences and the Museum of Paleontology at the University of Michigan, Ann Arbor, MI. Ivette Perfecto is a Professor in the School of Natural Resources and Environment at the University of Michigan, Ann Arbor, MI, USA.

Note: Catherine Badgley and Ivette Perfecto have not had an opportunity to respond to the following comments by Kenneth Cassman and Jim Hendrix.

Editorial response by Kenneth Cassman: can organic agriculture feed the world—science to the rescue?

During the past 30 years there has been a steady decrease in funding allocated to agricultural research in both developed and developing countries because of the widespread view that food insecurity is primarily caused by poverty and a lack of purchasing power rather than the inability to produce enough food[1]. However, these views are being challenged by three global mega-trends: (1) a steady decrease in arable land area suitable for intensive food crop production as a result of farmland conversion to urban, industrial and recreational uses, (2) a steady reduction in the relative rate of yield gain for the major cereal crops—yield gains that are falling below the projected rate of increase in cereal demand[2], and (3) a recent acceleration in the expansion of biofuel production from cereal, sugar and oilseed crops that will divert significant amounts of these crops from the human food supply[3].

Given these trends, the question of whether organic agriculture can meet current and future food demand at national and global levels is serious business—especially if the answer influences funding priorities for agricultural research[4,5]. Unfortunately, the paper by Badgley et al.[6] and the associated forum paper by Badgley and Perfecto, both in this issue of *RAFS* (Vol. 22, No. 2), do not answer this question because their analyses do not meet the minimum scientific requirements for comparing food production capacity in different crop production systems.

Scientific progress depends on published research in peer-reviewed journals—journals that require detailed specification of materials and methods used in the study to allow other scientists to challenge the conclusions and, if necessary, repeat the experiments. For comparisons of cropping systems with different management strategies, the following specifications and data are required:

1. *Definition of the systems to be compared.* For example, is the goal to compare organic and conventional systems when both utilize the best available technologies and crop rotations for a given field and region? In this case, researchers must strive to identify best management practices that optimize performance *of each* system separately with regard to input levels and timing of all crop and soil management operations for the specific soil and climatic conditions at the research site. In contrast, most comparisons of organic and conventional systems utilize a relatively customized set of practices for the organic system and standard 'recommended' practices for the conventional system, or practices thought to represent 'average' practices used by conventional crop producers in the region. The problem is that most conventional crop producers also customize crop and soil management practices to their production environment, which can vary substantially from field to field. Hence, a bias exists unless both systems receive the same degree of concern for optimization of all crop and soil management practices, for a given site, within the general guidelines of practices allowed for organic versus conventional systems.
2. *Specification of performance parameters as the basis of comparison.* The most relevant parameter to address the question of food security is food output per unit area-time. The time dimension is critical because organic systems often require rotations that include non-food crops, such as legume cover crops or lower-yielding legume crops, to provide nitrogen input from symbiotic nitrogen fixation. While yield of the same crop species grown in organic and conventional systems may be similar, total food output of the cropping system may differ depending on the rotation. Further specification of human edible calorie and/or protein yield per unit area-time is also helpful.
3. *Quantifying nutrient input levels and equalizing them as required.* Organic systems typically rely on manure or compost to satisfy crop nutrient demand and to maintain soil fertility. But release of organically bound nitrogen (N), phosphorus (P) and sulfur (S) in manure depends on biological processes controlled by temperature, moisture and microbial activity. In fact, only a portion of the applied nutrients contained in manure are released during the growing season in which the manure was applied. Likewise, the total amount of nutrients applied in manure is usually much greater than total nutrients applied in conventional systems receiving recommended rates of commercial fertilizer. Over time, the indigenous soil nutrient supply in organic systems often increases compared to that of conventional systems receiving recommended fertilizer rates. Moreover, manure contains all essential plant nutrients in addition to N, P and K—which are the primary nutrients applied in conventional systems. As a result, researchers comparing conventional and organic systems must carefully monitor crop nutrient status to ensure that the conventional system is not deficient in one or more essential nutrient because these deficiencies are easily corrected by application of the appropriate commercial fertilizer. Such measurements are especially important when organic versus conventional comparisons are conducted on soils that do not have high indigenous fertility levels.
4. *Appropriate experimental design and treatment replication.* Modern statistical methods were initially developed in the first half of the 20th century by agricultural scientists who recognized the challenge of making scientifically sound conclusions based on results from field experiments. Spatial and temporal variation in soil properties and climate require use of statistical theory in experimental design, treatment layout, and replication. Results from field studies that do not adhere to accepted statistical norms are not reliable.

The above specifications and data represent a minimum standard for making reliable comparisons of different

cropping systems. In my opinion, many of the studies cited by Badgley et al.[6] fail to meet these standards. Therefore, it is not possible to make sweeping conclusions about the potential for organic systems to feed the world by simply comparing yields between organic and conventional systems. Likewise, even more stringent and comprehensive specifications and data would be required for valid comparisons of the environmental impact of organic versus conventional systems—including the impact on soil quality, water quality as affected by nutrient losses, and greenhouse gas emissions. One cannot simply assume that organic systems are more environmentally sound because they do not use commercial fertilizers and pesticides.

In fairness to those who conducted most of the studies cited by Badgley et al.[6], the conduct of scientific studies of publishable quality does not appear to be their primary goal. Many seem to be demonstrations and informal trials. While such trials may have educational value, they are not an appropriate basis for scientific inquiry. In conclusion, the question of whether organic systems can feed the world remains unanswered.

Given the need to produce 60% more food by 2050 to meet demand from growth in both population and income, and to do so with less land and water for irrigation, there is an urgent need for a process of 'ecological intensification' of crop production systems[7]. A focus on existing conventional and emerging organic systems limits the possibilities. Instead, the emphasis should be on developing cropping systems that best contribute to a set of well-defined performance parameters that ensure adequate food supply, farm family income, and protection of environmental quality and natural resources. If a system meets these criteria, it should not matter whether it complies with rules prescribed for organic production systems, or any other arbitrary set of prescriptions for crop and soil management. The trend of decreasing funds for agricultural research in the public sector dictates a more efficient approach; one that focuses on outputs (broad sense—including environmental impact) from agricultural systems rather than on the type or source of inputs.

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Kenneth G. Cassman is the Director of the Nebraska Center for Energy Sciences Research and the B. Keith and Norma F. Heuermann Professor of Agronomy at the University of Nebraska, Lincoln, NE, USA.

Editorial response by Jim Hendrix

'Farming looks mighty easy when your plow is a pencil and you're a thousand miles from the corn field.' Dwight D. Eisenhower

When Eisenhower made the above observation in 1954, our nation was one to two generations removed from the realities of farming. In the intervening 53 years, certain segments of our society have come to idealize agriculture with a desire to connect to small-scale organic, family-operated farms and to demonize large-scale commercial farms. 'Organic agriculture and the global food supply', by Badgley et al., exemplifies the perspective of some scientists in the academic world who favor organic practices without having a grounded knowledge of the economics and drivers of food production.

I am a large-scale crop producer in the high plains region of Colorado, Kansas, Nebraska and Texas. We utilize center pivot irrigation on coarse sands, practice integrated pest management, and are early and consistent adaptors of technology to substitute capital for labor. We operate several farms utilizing conventional inorganic fertilizers, pesticides, crop rotation and minimal tillage to produce corn, edible beans and alfalfa. I am also involved with a large-scale organic farm and dairy-feeding operation in which we grow grain and alfalfa to produce organic milk. This combination of production practices, employing both organic and inorganic farming techniques, gives me insight into production costs and problems associated with both systems.

The Badgley et al. article misses the mark in several critical areas. In production agriculture, farmers respond to market signals and nitrogen is just one consideration. Organic fertilizer benefits are measured based upon N content and, in some cases, the content of other nutrients.

However, these nutrient additions are worth only the sum of their parts; organic nutrients convey no 'magical' properties. Because economics drive production, all sources of nitrogen will be used in the production of food, and combinations of organic and inorganic nitrogen are often used on the same farm. Likewise, the decision to include legumes in a crop rotation is made to maximize economic return and is based upon long-term fertility, current profitability, availability of labor and management, marketing opportunities and a host of other factors.

I question the validity of the statement that production per unit area is greater on small farms than on large farms. 'Large' farms generally maximize land, labor, machinery and management to lower the unit cost of the commodity being produced. Over time, commodities always trade at the average cost of production, leaving little room for producers who are high cost due to low volume.

It is elitist to condemn people to the drudgery of hand labor required on small organic farms; only those who have never done such work believe it is an employment solution. Throughout history, farm producers have sought productivity gains by substituting animal for human labor, designing and employing simple machines and, most recently, using information technology, remote monitoring and sophisticated machinery. It is unreasonable to believe that agriculture will return to hand labor to reduce unemployment or underemployment.

The final fallacy in the Badgley et al. article is the insinuation that organic farming is an advanced method of crop production that always leads to better soil tilth, less erosion and superior nutrition. In our experience, organic corn requires soil tillage prior to planting and cultivation during the growing season to control emerging seedling weeds. These operations destroy organic matter, reduce the water-holding capacity of our light sands and increase soil susceptibility to wind erosion. In contrast, our transgenic corn is planted into winter cover crops which are killed with herbicides after planting. Later, developing weeds are controlled with additional herbicides instead of mechanical cultivation. These conventional farming practices allow us to maintain a protective residue cover on the soil surface and increase soil organic matter inputs.

As a large-scale producer of organic and conventional food products, I would like to share a few insights into the crops that we produce. Generally speaking, as we move into more specialized crops and end products, organic farming becomes more difficult and expensive. For example, there is little difference in the cost of production or yield between organic and inorganic alfalfa. Insect and weed pressures are generally controlled with an early harvest, although this may change with new transgenic alfalfas that offer a longer stand life. On the other hand, dry edible beans are difficult to grow organically. They do not compete well with weeds and are subject to bacterial, fungal and rust infections and insect infestations which can cause considerable loss in both quantity and quality. Furthermore, organic bean yields are typically less than half of those for conventionally grown beans. The primary consumers of dry edible beans are generally unwilling to pay for the higher cost of organic production.

Production issues for organic corn fall somewhere between those for alfalfa and dry edible beans. Producers can access the highest yielding non-transgenic hybrids. In organic corn production, our limiting factor has not been nitrogen or other crop nutrients, even though total fertility costs are about 40% higher when compared to inorganic forms of fertilizers. Rather, soil insect pressure during stand establishment and the effective control of insects during the growing season have reduced organic corn yields to 80–85% of conventional. Overall, our cost per unit of production has been approximately 30% higher for organic compared to conventional corn.

In our operations, the economic driver for organic corn has been the production of a feed source for organic milk. Additional costs associated with organic production have been borne, to date, by the marketplace where wholesale organic milk is currently over twice the price of conventional. Consumers of organic milk believe there is economic and nutritional value in their purchase. Yet, using the latest advances in laboratory testing, we have been unable to demonstrate any difference in the nutrient content between our organic and conventionally produced milk. By purchasing organic milk and other organic products, I also believe that consumers feel they are supporting the idealized image of a small-scale organic, family-operated business. This is rarely the case.

Although economics will dictate how long we produce organic milk, we question the morality and sustainability of organic production. Given its inherently higher cost, are families purchasing less milk to the detriment of young children? Would these children be better served with larger quantities of nutritionally equivalent conventional milk? The same questions can be asked with regard to organic fruits and vegetables.

In the developed world of agriculture, producers respond to market incentives. Given sufficient net returns to attract adequate capital and management, producers will industrialize the production of organic food. We are not driven by ideological concepts, political correctness or environmental persuasions; we are driven by the marketplace. Farmers always respond to incentives in the market and will produce sufficient food using combinations of conventional and organic methods to maximize their individual net returns.

Jim Hendrix is a farmer and President of Progressive Ag Management, Inc., Wray, CO, USA.

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Organic agriculture and the global food supply

Catherine Badgley[1], Jeremy Moghtader[2,3], Eileen Quintero[2], Emily Zakem[4], M. Jahi Chappell[5], Katia Avilés-Vázquez[2], Andrea Samulon[2] and Ivette Perfecto[2,*]

[1]Museum of Palaeontology, University of Michigan, Ann Arbor, MI 48109, USA.
[2]School of Natural Resources and Environment, University of Michigan, Ann Arbor, MI 48109 USA.
[3]Department of Horticulture, Michigan State University, East Lansing, MI 48824, USA.
[4]School of Art and Design, University of Michigan, Ann Arbor, MI 48109, USA.
[5]Department of Ecology and Evolutionary Biology, University of Michigan, Ann Arbor, MI 48109, USA.
*Corresponding author: perfecto@umich.edu

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Abstract

The principal objections to the proposition that organic agriculture can contribute significantly to the global food supply are low yields and insufficient quantities of organically acceptable fertilizers. We evaluated the universality of both claims. For the first claim, we compared yields of organic versus conventional or low-intensive food production for a global dataset of 293 examples and estimated the average yield ratio (organic : non-organic) of different food categories for the developed and the developing world. For most food categories, the average yield ratio was slightly <1.0 for studies in the developed world and >1.0 for studies in the developing world. With the average yield ratios, we modeled the global food supply that could be grown organically on the current agricultural land base. Model estimates indicate that organic methods could produce enough food on a global *per capita* basis to sustain the current human population, and potentially an even larger population, without increasing the agricultural land base. We also evaluated the amount of nitrogen potentially available from fixation by leguminous cover crops used as fertilizer. Data from temperate and tropical agroecosystems suggest that leguminous cover crops could fix enough nitrogen to replace the amount of synthetic fertilizer currently in use. These results indicate that organic agriculture has the potential to contribute quite substantially to the global food supply, while reducing the detrimental environmental impacts of conventional agriculture. Evaluation and review of this paper have raised important issues about crop rotations under organic versus conventional agriculture and the reliability of grey-literature sources. An ongoing dialogue on these subjects can be found in the Forum editorial of this issue.

Key words: organic agriculture, conventional agriculture, organic yields, global food supply, cover crop

Introduction

Ever since Malthus, the sufficiency of the global food supply to feed the human population has been challenged. One side of the current debate claims that green-revolution methods—involving high-yielding plant and animal varieties, mechanized tillage, synthetic fertilizers and biocides, and now transgenic crops—are essential in order to produce adequate food for the growing human population[1–4]. Green-revolution agriculture has been a stunning technological achievement. Even with the doubling of the human population in the past 40 years, more than enough food has been produced to meet the caloric requirements for all of the world's people, if food were distributed more equitably[5]. Yet Malthusian doubts remain about the future. Indeed, given the projection of 9 to 10 billion people by 2050[6] and the global trends of increased meat consumption and decreasing grain harvests per capita[4], advocates argue that a more intensified version of green-revolution agriculture represents our only hope of feeding the world. Another side of the debate notes that these methods of food production have incurred substantial direct and indirect costs and may represent a Faustian bargain. The environmental price of green-revolution agriculture includes increased soil erosion, surface and groundwater contamination, release of greenhouse gases, increased pest resistance, and loss of biodiversity[7–14]. Advocates on this side argue that more sustainable methods of food production are essential over the long term[15–17].

If the latter view is correct, then we seem to be pursuing a short-term solution that jeopardizes long-term environmental sustainability. A central issue is the assertion that

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alternative forms of agriculture, such as organic methods, are incapable of producing as much food as intensive conventional methods do[1,3,5]. A corollary is that organic agriculture requires more land to produce food than conventional agriculture does, thus offsetting any environmental benefits of organic production[18]. Additionally, critics have argued that there is insufficient organically acceptable fertilizer to produce enough organic food without substantially increasing the land area devoted to agriculture[3].

Here, we evaluate the potential contribution of organic agriculture to the global food supply. Specifically, we investigate the principal objections against organic agriculture making a significant contribution—low yields and insufficient quantities of organic nitrogen fertilizers. The term 'organic' here refers to farming practices that may be called agroecological, sustainable, or ecological; utilize natural (non-synthetic) nutrient-cycling processes; exclude or rarely use synthetic pesticides; and sustain or regenerate soil quality. These practices may include cover crops, manures, compost, crop rotation, intercropping, and biological pest control. We are not referring to any particular certification criteria and include non-certified organic examples in our data.

Methods

We compiled data from the published literature about the current global food supply, comparative yields between organic and non-organic production methods, and biological nitrogen fixation by leguminous crops. These data were the basis for estimating the global food supply that could be grown by organic methods and the amount of nitrogen that could become available through increased use of cover crops as green manures.

Estimation of the global food supply

Estimation of the global food supply grown by organic methods involved compiling data about current global food production, deriving ratios of the yields obtained from organic versus non-organic production methods, and applying these yield ratios to current global production values.

Global food production. Summary data from the Food and Agricultural Organization (FAO) for 2001[19] document the current global food supply—grown primarily by conventional methods in most of the developed world and primarily by low-intensive methods in most of the developing world. The FAO provides estimates of the current food supply in 20 general food categories[19] which we modified for our study. We combined three pairs of categories (into sugars and sweeteners, vegetable oils and oilcrops, meat and offals). We omitted from consideration three categories (spices, stimulants, and 'miscellaneous'), because they contribute few calories and little nutritional value to the daily diet and lack comparative data for organic versus non-organic production. In addition, we reported data for seafood and 'other aquatic products' but did not estimate yield ratios for these categories, since most of these foods are currently harvested from the wild. Alcoholic beverages were reported since they contribute significantly to the average daily caloric intake, but no assessment of organic yields was made. The data presented for yield ratios pertain to ten categories covering the major plant and animal components of human diets.

Food-production data of the FAO include both commercial and domestic production and exclude losses during harvest. Pre-harvest crop losses are not included in the estimates; these losses may be substantial[20] but are not necessarily more serious for organic production, since a host of methods is available for managing pests[21,22]. For each country or region, the FAO data for the food supply available for human consumption take into account food production, exports, imports, and stocks, as well as losses of production to become livestock feed, seed, or waste[19]. 'Waste' refers to post-harvest loss during storage, transport, and processing. We compiled this information for the world, for developed countries, and for developing countries, following the FAO classification of countries as developed or developing.

Deriving yield ratios. We estimated the global organic food supply by multiplying the amount of food in the current (2001) food supply by a ratio comparing average organic : non-organic yields. Comparisons of organic to non-organic production are available for many plant foods and a few animal foods. For each of 293 comparisons of organic or semi-organic production to locally prevalent methods under field conditions, the yield ratio is the ratio of organic : non-organic production. A ratio of 0.96, for example, signifies that the organic yield is 96% that of the conventional yield for the same crop. The comparisons include 160 cases with conventional methods and 133 cases with low-intensive methods. Most examples are from the peer-reviewed, published literature; a minority come from conference proceedings, technical reports, or the Web site of an agricultural research station. Like Stanhill's 1990 survey of organic and conventional production[23], our data include numerous comparisons from paired farms and controlled experiments at research stations. The studies range in observation length from a single growing season to over 20 years. Despite the observation that yields following conversion from conventional to organic production initially decline and then may increase with time[24,25] (but see ref. 23), we included studies regardless of duration. All of Stanhill's examples (which are included here) were from the developed world, whereas our dataset also includes diverse examples from the developing world. No attempt was made to bias the results in favor of organic yields; many examples from developed and developing countries exhibit low comparative yields. We avoided generalizations based on country-wide or regional average yields by organic or conventional methods. Some examples are based on yields before and after conversion to organic methods on the same farm.

Table 1. Average yield ratio (organic : non-organic) and standard error (S.E.) for ten individual food categories recognized by the FAO[19] and three summary categories. Average yield ratio based on data from 91 studies (see Appendix 1 for data and sources). (A) All countries. (B) Developed countries. (C) Developing countries.

	(A) World			(B) Developed countries			(C) Developing countries		
Food category	***N***	**Av.**	**S.E.**	***N***	**Av.**	**S.E.**	***N***	**Av.**	**S.E.**
Grain products	171	1.312	0.06	69	0.928	0.02	102	1.573	0.09
Starchy roots	25	1.686	0.27	14	0.891	0.04	11	2.697	0.46
Sugars and sweeteners	2	1.005	0.02	2	1.005	0.02			
Legumes (pulses)	9	1.522	0.55	7	0.816	0.07	2	3.995	1.68
Oil crops and veg. oils	15	1.078	0.07	13	0.991	0.05	2	1.645	0.00
Vegetables	37	1.064	0.10	31	0.876	0.03	6	2.038	0.44
Fruits, excl. wine	7	2.080	0.43	2	0.955	0.04	5	2.530	0.46
All plant foods	266	1.325	0.05	138	0.914	0.02	128	1.736	0.09
Meat and offal	8	0.988	0.03	8	0.988	0.03			
Milk, excl. butter	18	1.434	0.24	13	0.949	0.04	5	2.694	0.57
Eggs	1	1.060		1	1.060				
All animal foods	27	1.288	0.16	22	0.968	0.02	5	2.694	0.57
All plant and animal foods	293	1.321	0.05	160	0.922	0.01	133	1.802	0.09

We grouped examples into ten general food categories and determined the average yield ratio for all cases in each food category. For the complete dataset and sources, see Appendix 1. Table 1 presents the average yield ratios of these food categories for all studies combined (the world), studies in developed countries, and studies in developing countries. If no data were available (e.g., tree nuts) for estimating global organic production, then we used the average yield ratio for all plant foods, or all animal foods where relevant. For individual studies in which several yield ratios were reported for a single crop (e.g., 0.80–2.00) grown under the same treatment, we took the average as the value for the study. When different treatments were described, we listed a value for each treatment. Averaging the yield ratios across each general food category reduced the effects of unusually high or low yield ratios from individual studies. As these studies come from many regions in developed and developing countries, the average yield ratios are based on a broad range of soils and climates. The average yield ratio is not intended as a predictor of the yield difference for a specific crop or region but as a general indicator of the potential yield performance of organic relative to other methods of production.

Studies in the global south usually demonstrate increases in yields following conversion to organic methods (Table 1C), but these studies are not comparable with those in the developed world. At present, agriculture in developing countries is generally less intensive than in the developed world. Organic production is often compared with local, resource-poor methods of subsistence farming, which may exhibit low yields because of limited access by farmers to natural resources, purchased inputs, or extension services. While adoption of green-revolution methods has typically increased yields, so has intensification by organic methods[26]. Such methods more often result in non-certified than in certified organic production, since most food produced is for local consumption where certification is not at issue[27]. Data from these studies are relevant for our inquiry, which seeks quantitative comparisons between organic production and prior methods, whether by conventional or subsistence practices, since both prevailing methods contribute to global food production.

Estimating the global food supply. Using the average yield ratio for each food category, we estimated the amount of food that could be grown organically by multiplying the amount of food currently produced times the average yield ratio (Tables 2 and 3). Following the FAO methodology[19], this estimate was then proportionally reduced for imports, exports, and losses (e.g., Table 2, column D) to give the estimated organic food supply after losses (e.g., Table 2, column G), which is the food supply available for human consumption. We assumed that all food currently produced is grown by non-organic methods, as the global area of certified organic agriculture is only 0.3%[28].

We constructed two models of global food production grown by organic methods. Model 1 applied the organic : non-organic (conventional) yield ratios derived from studies in developed countries to the entire agricultural land base (Table 2). This model effectively assumes that, if converted to organic production, the low-intensity agriculture present in much of the developing world would have the same or a slight reduction in yields that has been reported for the developed world, where green-revolution methods now dominate. Model 2 applied the yield ratios derived from studies in the developed world to food production in the developed world, and the yield ratios derived from studies in the developing world to food production in the developing world (Table 3). The sum of these separate estimates provides the global estimate.

Table 2. Actual (2001) food supply and estimates for Model 1. Data for world food supply from FAO Statistical Database[19].

(A) Food category	(B) Actual world food production	(C) Actual food supply after losses	(D) Supply as proportion of production (C/B)	(E) Average yield ratio (Table 1)	(F) Estimated organic food production (B × E)	(G) Estimated organic food supply after losses (D × F)
Units	1000 Mg	1000 Mg			1000 Mg	1000 Mg
Grain products	1,906,393	944,611	0.50	0.928	1,769,133	876,599
Starchy roots	685,331	391,656	0.57	0.891	610,630	348,965
Sugars and sweeteners	1,666,418	187,040	0.11	1.005	1,674,917	187,975
Legumes (pulses)	52,751	32,400	0.61	0.816	43,044	26,438
Tree nuts	7,874	7,736	0.98	0.914[1]	7,213	7,070
Oil crops and vegetable oils	477,333	110,983	0.23	0.991	472,559	109,984
Vegetables	775,502	680,802	0.88	0.876	679,340	596,383
Fruits, excl. wine	470,095	372,291	0.79	0.955	448,940	355,538
Alcoholic beverages	230,547	199,843	0.87			
Meat and offal	252,620	247,446	0.98	0.988	249,588	244,476
Animal fats	32,128	19,776	0.62	0.968[2]	31,100	19,143
Milk, excl. butter	589,523	479,345	0.81	0.949	559,457	454,898
Eggs	56,965	50,340	0.88	1.060	60,383	53,360
Seafood	124,342	95,699	0.77			
Other aquatic products	10,579	8,514	0.80			
Average for all foods				0.922		

[1] Average yield ratio for all plant foods (developed countries) was used, since no comparative yield data were available for this food category.
[2] Average yield ratio for all animal foods (developed countries) was used, since no comparative data were available for this food category.
Mg = megagram = metric ton.

In Model 1, the standard error of the estimate was calculated for an affine transformation (i.e., rescaled to world food production)[29]. In Model 2, the estimated global organic food production was the sum of two regional calculations—the yield ratios from the developed world times the current food production in the developed world and the yield ratios from the developing world times the current food production in the developing world. The standard error of the global estimate was determined for the sum of two independent random variables[29].

For Model 2, we did not adjust for the amount of imported food in each food category. These amounts ranged from 4.9 to 75.8% (imported as a proportion of total food supply before losses) for the developed-world food supply and from 0.7 to 22.7% for the developing-world food supply[19]. Adjusting for imports in Model 2 would elevate slightly to greatly the estimates of the organic food supply in developed countries (Table 3, column F, because a proportion of the actual food supply would be multiplied by the higher average yield ratios for developing countries) and would diminish slightly the estimates of the organic food supply in the developing world (Table 3, column K, because a proportion of the actual food supply would be multiplied by the lower average yield ratios for the developed world). The overall results would be qualitatively similar.

Additional model assumptions. Both models were based on the pattern of food production and the amount of land devoted to crops and pasture in 2001. The models estimate the kinds and relative amounts of food that are currently produced and consumed, including the same pattern of total and per-capita consumption of meat, sugars, and alcoholic beverages. Additional assumptions include (1) the same proportion of foods grown for animal feed (e.g., 36% of global grain production), (2) the same proportion of food wasted (e.g., 10% of starchy roots), and (3) the same nutritional value of food (e.g., for protein and fat content in each food category), even though changes in some of these practices would benefit human or environmental health. Finally, we made no assumptions about food distribution and availability, even though changes in accessibility are necessary to achieve global food security. These assumptions establish the boundary conditions for the models but are not intended as an assessment of the sustainability of the current global food system.

Calories per capita

The calories per capita resulting from Models 1 and 2 were estimated by multiplying the average yield ratios (organic : non-organic) in each food category by the FAO estimate of per-capita calories currently available in that food category[19].

Nitrogen availability with cover crops

The main limiting macronutrient for agricultural production is biologically available nitrogen (N) in most areas, with

Table 3. Actual (2001) food supply and estimates for Model 2. Data for world food supply from FAO Statistical Database[19]; data for yield ratios from Table 1.

(A) Food category	(B) Actual food production	(C) Actual food supply after losses	(D) Food supply as proportion of production	(E) Av. yield ratio	(F) Est. organic food supply after losses	(G) Actual food production	(H) Actual food supply after losses	(I) Food supply as proportion of production	(J) Av. yield ratio	(K) Est. organic food supply after losses	(L) World, est. organic food supply after losses (F + K) World
	Developed countries					Developing countries					
Units	1000 Mg	1000 Mg		Ratio	1000 Mg	1000 Mg	1000 Mg		Ratio	1000 Mg	1000 Mg
Grain products	879,515	178,973	0.20	0.928	166,087	1,026,878	765,638	0.75	1.573	1,204,348	1,370,435
Starchy roots	176,120	96,754	0.55	0.891	86,207	509,211	294,902	0.58	2.697	795,352	881,559
Sugars and sweeteners	332,987	56,274	0.17	1.005	56,555	1,333,430	130,766	0.10	1.736[4]	227,010	283,565
Legumes (pulses)	15,122	1,679	0.11	0.816	1,370	37,628	30,721	0.82	3.995	122,729	124,099
Tree nuts	2,194	3,336	1.52[1]	0.914[2]	3,049	5,680	4,400	0.77	1.736[4]	7,638	10,687
Oil crops and veg. oils	175,591	25,316	0.14	0.991	25,089	301,741	85,667	0.28	1.645	140,921	166,010
Vegetables	163,815	150,127	0.92	0.876	131,511	611,687	530,675	0.87	2.038	1,081,516	1,213,027
Fruits, excl. wine	123,276	108,224	0.88	0.955	103,354	346,818	264,067	0.76	2.530	668,088	771,443
Alcoholic beverages	122,376	110,827	0.91			108,172	89,016	0.82			
Meat and offal	111,595	106,865	0.96	0.988	105,583	141,024	140,581	1.00	1.802[5]	253,327	358,909
Animal fats	21,420	10,881	0.51	0.968[3]	10,533	10,708	8,895	0.83	1.802[5]	16,029	26,561
Milk, excl. butter	347,782	260,699	0.75	0.949	247,404	241,742	218,645	0.90	2.694	589,030	836,434
Eggs	18,645	16,697	0.90	1.060[3]	17,699	38,320	33,643	0.88	1.802[5]	60,625	78,323
Seafood	30,894	30,401	0.99			93,447	65,298	0.70			
Other aquatic products	958	234	0.24			9,621	8,280	0.86			

[1] Ratio is greater than 1.0 because of imports. All values in column (C) include imports but these are typically a small proportion of food production; for tree nuts, however, about one-third of the supply for the developed world is imported from the developing world.
[2] Average yield ratio for all plant foods (developed countries) was used, since no comparative yield data were available for this food category.
[3] Average yield ratio for all animal foods (developed countries) was used, since no comparative yield data were available for this food category.
[4] Average yield ratio for all plant foods (developing countries) was used, since no comparative yield data were available for this food category.
[5] Average yield ratio (developing countries) for all plant and animal foods was used, since no comparative yield data were available for this food category; the average for all foods was a more conservative estimate than the average for animal foods alone.

phosphorus limiting in certain tropical regions[30]. For phosphorus and potassium, the raw materials for fertility in organic and conventional systems come largely from mineral sources[31] and are not analyzed here.

Nitrogen amendments in organic farming derive from crop residues, animal manures, compost, and biologically fixed N from leguminous plants[32]. A common practice in temperate regions is to grow a leguminous cover crop during the winter fallow period, between food crops, or as a relay crop during the growing season. Such crops are called green manures when they are not harvested but plowed back into the soil for the benefit of the subsequent crop. In tropical regions, leguminous cover crops can be grown between plantings of other crops and may fix substantial amounts of N in just 46–60 days[33]. To estimate the amount of N that is potentially available for organic production, we considered only what could be derived from leguminous green manures grown between normal cropping periods. Nitrogen already derived from animal manure, compost, grain legume crops, or other methods was excluded from the calculations, as we assumed no change in their use. The global estimate of N availability was determined from the rates of N availability or N-fertilizer equivalency reported in 77 studies—33 for temperate regions and 44 for tropical regions, including three studies from arid regions and 18 studies of paddy rice. N availability values in $kg\,ha^{-1}$ were obtained from studies as either 'fertilizer-replacement value,' determined as the amount of N fertilizer needed to achieve equivalent yields to those obtained using N from cover crops, or calculated as 66% of N fixed by a cover crop becoming available for plant uptake during the growing season following the cover crop[34]. The full dataset and sources are listed in Appendix 2. We estimated the total amount of N available for plant uptake by multiplying the area currently in crop production (but not already in leguminous forage production—large-scale plantings of perennial legume systems) by the average amount ($kg\,ha^{-1}$) of N available to the subsequent crop from leguminous crops during winter fallow or between crops (Table 4, Appendix 2).

Results and Discussion

Estimates of food and caloric production under organic agriculture

Figure 1 compares the estimates from Models 1 and 2 to the current food supply. According to Model 1, the estimated organic food supply is similar in magnitude to the current food supply for most food categories (grains, sweeteners, tree nuts, oil crops and vegetable oils, fruits, meat, animal fats, milk, and eggs). This similarity occurs because the average yield ratios for these categories range from 0.93 to 1.06 (Figure 1, Tables 1B and 2). For other food categories (starchy roots, legumes, and vegetables), the average yield ratios range from 0.82 to 0.89, resulting in somewhat lower production levels. The average yield ratio for all 160 examples from developed countries is 0.92, close to Stanhill's average relative yield of 0.91[23]. According to Model 2, the estimated organic food supply exceeds the current food supply in all food categories, with most estimates over 50% greater than the amount of food currently produced (Figure 1). The higher estimates in Model 2 result from the high average yield ratios of organic versus current methods of production in the developing world (Tables 1C and 3). The average yield ratio for the 133 examples from the developing world is 1.80. We consider Model 2 more realistic because it uses average yield ratios specific to each region of the world.

These two models likely bracket the best estimate of global organic food production. Model 1 may underestimate the potential yield ratios of organic to conventional production, since many agricultural soils in developed countries have been degraded by years of tillage, synthetic fertilizers, and pesticide residues. Conversion to organic methods on such soils typically results in an initial decrease

Table 4. Estimated nitrogen available for plant uptake from biological nitrogen fixation with leguminous cover crops, for the world and the US. For A, and F, data are from FAO Statistical Data Base[19] and USDA National Agriculture Statistics[35]; for B, data for the world are from Gallaway et al., 1995[36], and for the US from USDA-ERS[37] and the USDA National Agriculture Statistics[35]; for D, data are from sources listed in Appendix 2. Estimates are based on land area not currently in leguminous forage production.

		World	US
A	Area of total cropland	1513.2 million ha	177.3 million ha
B	Area in leguminous forage production	170.0 million ha	36.0 million ha
C	Area remaining for use in cover crops (A–B)	1362.1 million ha	141.3 million ha
D	Average N availability or fertilizer-equivalence from winter and off-season cover crops	102.8 kg N ha^{-1} yr^{-1} (n = 77, S.D. = 71.8)	95.1 kg N ha^{-1} yr^{-1} (n = 32, S.D. = 37.5)
E	Estimated N available from additional cover crops without displacing production (C × D)	140.0 million Mg N	13.4 million Mg N
F	Total synthetic N fertilizer in current use by conventional agriculture	82.0 million Mg N	10.9 million Mg N
G	Estimated N fixed by cover crops in excess of current synthetic fertilizer use (E–F)	58.0 million Mg N	2.5 million Mg N

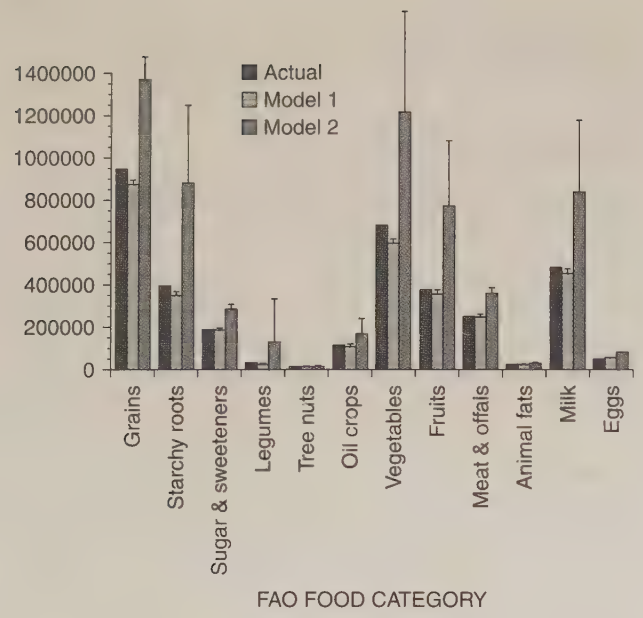

Figure 1. Estimates of the global food supply from two models of organic production compared with the actual food supply in 2001. Standard errors are given for food categories with multiple studies of yield ratios (see Table 1 and Appendix 1).

in yields, relative to conventional methods, followed by an increase in yields as soil quality is restored[7,25]. Model 2 may overestimate the yield ratios for the developing world to the extent that green-revolution methods are practiced.

Both models suggest that organic methods could sustain the current human population, in terms of daily caloric intake (Table 5). The current world food supply after losses[19] provides 2786 kcal person^{-1} day^{-1}. The average caloric requirement for a healthy adult[38] is between 2200 and 2500 kcal day^{-1}. Model 1 yielded 2641 kcal person^{-1} day^{-1}, which is above the recommended value, even if slightly less than the current availability of calories. Model 2 yielded 4381 kcal person^{-1} day^{-1}, which is 57% greater than current availability. This estimate suggests that organic production has the potential to support a substantially larger human population than currently exists. Significantly, both models have high yields of grains, which constitute the major caloric component of the human diet. Under Model 1, the grain yield is 93% that of current production. Under Model 2, the grain yield is 145% that of current production (Table 5).

The most unexpected aspect of this study is the consistently high yield ratios from the developing world (Table A1, Appendix 1). These high yields are obtained when farmers incorporate intensive agroecological techniques, such as crop rotation, cover cropping, agroforestry, addition of organic fertilizers, or more efficient water management[16,39]. In some instances, organic-intensive methods resulted in higher yields than conventional methods for the same crop in the same setting (e.g., the system of rice intensification (SRI) in ten developing countries[39]). Critics have argued that some of these examples exceed the intrinsic yield limits set by crop genetics and the environmental context[40]. (Such controversy surrounds the 'SRI' and our data include studies from both sides of this controversy.) Yet alternative agricultural methods may elicit a different pathway of gene expression than conventional methods do[41]. Thus, yield limits for conventionally grown crops may not predict the yield limits under alternative methods.

Crop rotation and yield-time adjustment

Organic grain production frequently uses a different rotation system than conventional production. For example, it is common in organic systems to have a three or four-year rotation (with legumes or other crops) for corn, while the conventional rotation often involves planting corn every other year. In situations like this, it is difficult to make yield comparisons between organic and conventional systems without some sort of time adjustment. Although the high variation among rotation systems worldwide makes it impossible to provide a general time–yield adjustment, evaluating potential differences in performance is important. A thorough evaluation of the rotation effect requires knowledge of the plot-to-plot yield differences between organic and conventional production and the rate of decline of both organic and conventional production as a function of the rotation sequence—information that has not yet been experimentally demonstrated. While rotations would undoubtedly differ under a global organic production system, we have no basis for concluding that this system would be unable to provide enough grain to feed the world.

Organic nitrogen fertilizer

In 2001, the global use of synthetic N fertilizers was 82 million Mg (metric ton)[19]. Our global estimate of N fixed by the use of additional leguminous crops as fertilizer is 140 million Mg, which is 58 million Mg greater than the amount of synthetic N currently in use (Table 4). Even in the US, where substantial amounts of synthetic N are used in agriculture, the estimate shows a surplus of available N through the additional use of leguminous cover crops between normal cropping periods. The global estimate is based on an average N availability or N-fertilizer equivalency of 102.8 kg N ha^{-1} (S.D. 71.8, $n = 76$, Table A2, Appendix 2). For temperate regions, the average is 95.1 kg N ha^{-1} (S.D. 36.9, $n = 33$) and for tropical regions, the average is 108.6 kg N ha^{-1} (S.D. 99.2, $n = 43$). These rates of biological N fixation and release can match N availability with crop uptake and achieve yields equivalent to those of high-yielding conventionally grown crops[42]. In temperate regions, winter cover crops grow well in fall after harvest and in early spring before planting of the main food crop[43]. Research at the Rodale Institute (Pennsylvania, USA) showed that red clover and hairy vetch as winter covers in an oat/wheat–corn–soybean rotation with no additional fertilizer inputs achieved yields comparable to those in conventional controls[24,25,44]. Even

Table 5. Caloric values for the actual food supply (2001, data from FAO[19]) and for the organic food supply estimated in Models 1 and 2 (Tables 2 and 3). For alcoholic beverages, seafood, and other aquatic products, no change in caloric intake was assumed.

Food category	Actual food supply after losses	Actual per capita supply	Model 1 results	Ratio of model/ actual	Est. per capita supply, Model 1	Model 2 results	Ratio of model/ actual	Est. per capita supply, Model 2
Units	1000 Mg	Kcal day^{-1}	1000 Mg		Kcal day^{-1}	1000 Mg		Kcal day^{-1}
Grain products	944,611	1335.3	876,599	0.93	1239.1	1,370,435	1.45	1937.2
Starchy roots	391,656	146.8	348,965	0.89	130.8	881,559	2.25	330.4
Sugars and sweeteners	187,040	247.7	187,975	1.01	249.0	283,565	1.52	375.6
Legumes (pulses)	32,400	53.8	26,438	0.82	43.9	124,099	3.83	205.9
Tree nuts	7,736	8.9	7,070	0.91	8.2	10,687	1.38	12.3
Oil crops and veg. oils	110,983	326.4	109,984	0.99	323.1	166,010	1.50	488.2
Vegetables	680,802	72.7	596,383	0.88	63.7	1,213,027	1.78	129.6
Fruits, excl. wine	372,291	77.8	355,538	0.96	74.3	771,443	2.07	161.2
Alcoholic beverages	199,843	64.0			64.0			64.0
Meat and offals	247,446	211.1	244,476	0.99	208.6	358,909	1.45	306.2
Animal fats	19,776	61.2	19,143	0.97	59.2	26,561	1.34	82.2
Milk, excl. butter	479,345	119.7	454,898	0.95	113.6	836,434	1.74	208.9
Eggs	50,340	32.3	53,360	1.06	34.2	78,323	1.56	50.2
Seafood	95,699	27.4			27.4			27.4
Other aquatic prod.	8,514	1.4			1.4			1.4
Total		2786.4			2640.7			4380.6

in arid and semi-arid tropical regions, where water is limiting between periods of crop production, drought-resistant green manures, such as pigeon peas or groundnuts, can be used to fix N[26,45,46]. Use of cover crops in arid regions has been shown to increase soil moisture retention[47], and management of dry season fallows commonly practiced in dry African savannas can be improved with the use of N-fixing cover crops for both N-fixation and weed control[48]. Areas in sub-Saharan Africa which currently use only very small amounts of N fertilizer (9 kg ha^{-1}, much of it on non-food crops[48]) could easily fix more N with the use of green manures, leading to an increase in N availability and yields in these areas[26]. In some agricultural systems, leguminous cover crops not only contribute to soil fertility but also delay leaf senescence and reduce the vulnerability of plants to disease[30].

Our estimates of N availability from leguminous cover crops do not include other practices for increasing biologically fixed N, such as intercropping[49], alley cropping with leguminous trees[50], rotation of livestock with annual crops[32], and inoculation of soil with free-living N-fixers[51]—practices that may add considerable N fertility to plant and animal production[52]. In addition, rotation of food-crop legumes, such as pulses, soy, or groundnuts, with grains can contribute as much as 75 kg N ha^{-1} to the grains that follow the legumes[33].

These methods can increase the N-use efficiency by plants. Since biologically available N is readily leached from soil or volatilized if not taken up quickly by plants, N use in agricultural systems can be as low as 50%[53]. Organic N sources occur in more stable forms in carbon-based compounds, which build soil organic matter and increase the amount of N held in the soil[25,54]. Consequently, the amount of N that must be added each year to maintain yields may actually decrease, because the release of organic N fixed in one season occurs over several years[30].

These results imply that, in principle, no additional land area is required to obtain enough biologically available N to replace the current use of synthetic N fertilizers. Although this scenario of biological N fixation is simple, it provides an assessment, based on available data, for one method of organic N-fertility production that is widely used by organic farmers and is fairly easy to implement on a

large scale. This scenario is not intended to be prescriptive for any particular rotation or location, but to demonstrate the possibility of this type of cover-cropping system to fix large quantities of N without displacing food crops or expanding land area. The Farm Systems Trial at the Rodale Institute uses legume cover crops grown between main crops every third year as the only source of N fertility and reports comparable grain yields to those of conventionally managed systems, while using non-legume winter cover crops in other years to maintain soil quality and fertility and to suppress weeds (R. Seidel and P. Hepperly, personal communication, 2006). In practice, a range of methods acceptable in organic agriculture provides critical flexibility in N-management[32], including many sources other than cover crops. Although some environmental and economic circumstances pose challenges to reliance on leguminous fertilizers[55], the full potential of leguminous cover crops in agriculture is yet to be utilized. Implementation of existing knowledge could increase the use of green manures in many regions of the world[56]. Future selection for crop varieties and green manures that have higher rates of N fixation, especially in arid or semi-arid regions, and perform well under N-limiting conditions, as well as for improved strains of N-fixing symbionts, combined with reductions in the amount of N lost from legume-based production systems, and increases in the planting of legumes, hold great promise for increasing the role of biological N-fixation in fertility management[57]. The capacity for increased reliance on legume fertilizers would be even greater with substantive changes in the food system, such as reduction of food waste and feeding less grain to livestock[56].

Prospects for More Sustainable Food Production

Our results suggest that organic methods of food production can contribute substantially to feeding the current and future human population on the current agricultural land base, while maintaining soil fertility. In fact, the models suggest the possibility that the agricultural land base could eventually be reduced if organic production methods were employed, although additional intensification via conventional methods in the tropics would have the same effect. Our calculations probably underestimate actual output on many organic farms. Yield ratios were reported for individual crops, but many organic farmers use polycultures and multiple cropping systems, from which the total production per unit area is often substantially higher than for single crops[48,58]. Also, there is scope for increased production on organic farms, since most agricultural research of the past 50 years has focused on conventional methods. Arguably, comparable efforts focused on organic practices would lead to further improvements in yields as well as in soil fertility and pest management. Production per unit area is greater on small farms than on large farms in both developed and developing countries[59]; thus, an increase in the number of small farms would also enhance food production. Finally, organic production on average requires more hand labor than does conventional production, but the labor is often spread out more evenly over the growing season[25,60–62]. This requirement has the potential to alleviate rural unemployment in many areas and to reduce the trend of shantytown construction surrounding many large cities of the developing world.

The Millennium Ecosystem Assessment[17] recommends the promotion of agricultural methods that increase food production without harmful tradeoffs from excessive use of water, nutrients, or pesticides. Our models demonstrate that organic agriculture can contribute substantially to a more sustainable system of food production. They suggest not only that organic agriculture, properly intensified, could produce much of the world's food, but also that developing countries could increase their food security with organic agriculture. The results are not, however, intended as forecasts of instantaneous local or global production after conversion to organic methods. Neither do we claim that yields by organic methods are routinely higher than yields from green-revolution methods. Rather, the results show the potential for serious alternatives to green-revolution agriculture as the dominant mode of food production.

In spite of our optimistic prognosis for organic agriculture, we recognize that the transition to and practice of organic agriculture contain numerous challenges—agronomically, economically, and educationally. The practice of organic agriculture on a large scale requires support from research institutions dedicated to agroecological methods of fertility and pest management, a strong extension system, and a committed public. But it is time to put to rest the debate about whether or not organic agriculture can make a substantial contribution to the food supply. It can, both locally and globally. The debate should shift to how to allocate more resources for research on agroecological methods of food production and how to enhance the incentives for farmers and consumers to engage in a more sustainable production system. Finally, production methods are but one component of a sustainable food system. The economic viability of farming methods, land tenure for farmers, accessibility of markets, availability of water, trends in food consumption, and alleviation of poverty are essential to the assessment and promotion of a sustainable food system.

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Appendix 1: Yield Ratios

The studies used to estimate the yield ratios for different food categories in Table 1 come from 91 sources in Table A1 describing results from experiments at research stations, comparisons of paired farms, and comparisons before and after the transition to organic production. The data come from 53 countries and 12 US states. Some comparisons during the transition to organic production come from surveys, especially in the data for the developing world. Data range in observation length from one growing season to over 20 years. Despite the observation that yields following conversion from conventional to organic production initially decline and then tend to increase over time[24], we did not omit studies of short duration so as not to bias estimates of relative yield. We included data from previous comparisons of organic and conventional production, notably Stanhill[23], Lampkin and Padel[63], and McDonald et al.[64] for the SRI in the developing world. Over 80% of the examples listed come directly from peer-reviewed journal articles or are cited or figured in them. The remainder come from technical books, conference proceedings, technical reports from universities, government agencies or independent research foundations, or the Web site of a university research station.

For the developing world, there are fewer controlled comparisons of organic versus non-organic methods than for the developed world. Much of our data in Table A1B comes from one source (Pretty and Hine[65]), which is a compilation from surveys in developing countries of yield comparisons before and after farmers adopted specific agroecological practices. In order to determine whether the survey data biased our results, we tested the hypothesis that the average yield ratio based on survey data and unreported methods differed significantly from the average yield ratio based on experimental data and quantitative comparisons of paired farms. The only food category with a substantial sample size of yield ratios in both categories of studies was grains ($n = 102$). We subdivided grains into rice and all other grains, because more than half of our data concern rice but these data are quite unequally distributed between the two categories of studies. For rice ($n = 61$), a t-test ($p = 0.55$) comparing the average yield ratios from surveys and unreported methods versus experiments and paired farms failed to reject the null hypothesis that the average yield ratios do not differ significantly. For all other grains ($n = 41$), a t-test ($p = 0.45$) also failed to reject the null hypothesis. Thus, we concluded that the survey data have not unduly biased our results for the developing world. (No data for the developed world come from surveys.)

Table A1. Yield ratios of organic production : non-organic production, grouped by FAO food categories analyzed in the text. (A) Data from developed countries, where comparisons are between organic and conventional (green-revolution) production methods. (B) Data from developing countries, where comparisons are primarily between organic and non-intensive methods.

(A) Developed countries

Crop	Yield ratio	Location	Reference
Grains			
Barley, summer	1.03	Germany	Keopf, H.H., Pettersson, B.D., and Schaumann, W. 1976. Biodynamic Agriculture. The Anthroposophic Press, Spring Valley, NY.
Barley, winter	1.14	Germany	Keopf, H.H. et al. 1976. Op. cit.
Barley	0.68	New Zealand	Nguyen, M.L. and Haynes, R.J. 1995. Energy and labour efficiency for three pairs of conventional and alternative mixed cropping (pasture-arable) farms in Canterbury, New Zealand. Agriculture, Ecosystems, and Environment 52:163–172.
Barley	0.78	Sweden	Dlouhy, J. 1981. Alternative forms of agriculture—quality of plant products from conventional and biodynamic growing. Report 91, Department of Plant Husbandry, Swedish University of Agricultural Sciences, Uppsala.
Barley	0.65	Sweden	Dlouhy, J. 1981. Op. cit.
Barley	0.75	Switzerland	Eidg. Forschungsanstalt für Betriebswirtschaft und Landtechnik. 1993. Bericht über biologisch bewirtschaftete Betriebe 1991. Tänikon, Switzerland.
Barley	0.86	Switzerland	Steinmann, R. 1983. Biological Agriculture—A Bookkeeping Comparison. Report No. 19, Swiss Federal Research Station for Farm Management and Agricultural Engineering, Tänikon, Switzerland.
Corn, sweet	0.82	Canada, Nova Scotia	Warman, P.R. and Havard, K.A. 1998. Yield, vitamin and mineral contents of organically and conventionally grown potatoes and sweet corn. Agriculture, Ecosystems and Environment 68:207–216.
Corn	1.16	Canada, Ontario	Stonehouse, P. 1991. Economics of Weed Control in Alternative Farming Systems. In Proceedings of the 5th REAP Conference. McGill University, Macdonald Campus, Quebec.

Table A1. Continued.

Crop	Yield ratio	Location	Reference
Corn, sweet	0.60	Canada, Ontario	Sellen, D., Tolman, J.H., McLeod, D., Weersink, A., and Yiridoe, E. 1993. Economics of Organic and Conventional Horticulture Production. Working Paper, Department of Agricultural Economics and Business, University of Guelph, Guelph, Ontario.
Corn	0.89	Switzerland	Steinmann, R. 1983. Op. cit.
Corn	0.94	US, 7 states	Liebhardt, B. 2001. Get the facts straight: organic agriculture yields are good. Organic Farming Research Foundation Information Bulletin 10, 1–5. Santa Cruz, CA. Available at Web site: http://www.ofrf.org/publications/news/IB10.pdf
Corn	0.95	US, California	Clark, M.S., Ferris, H., Klonsky, K., Lanini, W.T., van Bruggen, A.H.C., and Zalom, F.G. 1998. Agronomic, economic, and environmental comparison of pest management in conventional and alternative tomato and corn systems in northern California. Agriculture, Ecosystems and Environment 68:51–71.
Corn	1.01	US, California	Poudel, D.D., Horwath, W.R., Lanini, W.T., Temple, S.R., and van Bruggen, A.H.C. 2002. Comparison of soil N availability and leaching potential, crop yields and weeds in organic, low-input and conventional farming systems in northern California. Agriculture, Ecosystems and Environment 90:125–137.
Corn	0.92	US, Iowa	Delate, K. and Cambardella, C.A. 2004. Agroecosystem performance during transition to certified organic grain production. Agronomy Journal 96:1288–1298.
Corn	0.92	US, midwest	Lockeretz, W., Shearer, G., and Kohl, D.H. 1981. Organic farming in the corn belt. Science 211:540–547.
Corn	0.91	US, Minnesota	Porter, P., Huggins, D., Perillo, C., Quiring, S., and Crookston, R. 2003. Organic and other management strategies with two- and four-year crop rotations in Minnesota. Agronomy Journal 95:233–244.
Corn	0.92	US, Nebraska	Sahs, W.W., Lesoing, G.W., and Francis, C.A. 1992. Rotation and manure effects on crop yields and soil characteristics in eastern Nebraska. Agronomy Abstracts 84:155.
Corn	0.93	US, New Jersey	Brumfield, R.G., Rimal, A., and Reiners, S. 2000. Comparative cost analyses of conventional, integrated crop management, and organic methods. HortTechnology 10:785–793.
Corn	1.30	US, Ohio	National Research Council. 1989. Alternative Agriculture. National Academy Press, Washington, DC.
Corn	1.17	US, Pennsylvania	National Research Council. 1989. Op. cit.
Corn	0.86	US, Pennsylvania	Pimentel, D., Hepperly, P., Hanson, J., Douds, D., and Seidel, R. 2005. Environmental, energetic, and economic comparisons of organic and conventional farming systems. Bioscience 55:573–582.
Corn	0.89	US, Pennsylvania	Pimentel, D. et al. 2005. Op. cit.
Corn	0.84	US, South Dakota	Smolik, J.D., Dobbs, T.L., and Rickerl, D.H. 1995. The relative sustainability of alternative, conventional, and reduced-till farming systems. American Journal of Alternative Agriculture 10:25–35.
Corn	0.95	US, South Dakota	Dobbs, T. and Smolik, J.D. 1996. Productivity and profitability of conventional and alternative farming systems: A long-term on-farm paired comparison. Journal of Sustainable Agriculture 9:63–77.
Corn	1.04	US, western corn belt	Roberts, K.J., Warnken, F., and Schneeberger, K.C. 1979. The economics of organic crop production in the Western corn belt. Agricultural Economics Paper No. 1979-6. Department of Agricultural Economics, University of Missouri, Columbia, MO. p. 63–101.
Grains	1.24	Germany	Keopf, H.H. 1981. The principles and practice of biodynamic agriculture. In B. Stonehouse (ed.). Biological Husbandry. Butterworths, London. p. 237–250.
Oats	1.21	Germany	Koepf, H.H. et al. 1976, Op. cit.
Oats	0.85	Switzerland	Steinmann, R. 1983, Op. cit.
Oats	1.00	US, midwest	Lockeretz, W. et al. 1981. Op. cit.
Oats	1.23	US, Ohio	National Research Council. 1989. Op. cit.
Oats	0.73	US, western corn belt	Roberts, K.J. et al. 1979. Op. cit.
Oats	0.85	UK	Trewavas, A. 2004. A critical assessment of organic farming-and-food assertions with particular respect to the UK and the potential environmental benefits of no-till agriculture. Crop Protection 23:757–781.

Table A1. Continued.

Crop	Yield ratio	Location	Reference
Rice	0.85	Spain	Scialabba, N. El-H. and Hattam, C. (eds). 2002. Organic Agriculture, Environment, and Food Security. FAO, Rome.
Rye	1.26	Germany	Koepf, H.H. et al. 1976. Op. cit.
Rye	0.94	Germany	Raupp, J. 1996. Quality investigations with products of the long-term fertilization trial in Darmstadt. In J. Raupp (ed.). Quality of Plant Products Grown with Manure Fertilization. Vol. 9. Institute for Biodynamic Research, Darmstadt. p. 13–33.
Rye	0.96	Germany	Raupp, J. 1996. Op. cit.
Rye	0.75	Germany	Raupp, J. 1996. Op. cit.
Rye	0.78	Germany	Raupp, J. 1996. Op. cit.
Rye	0.81	Switzerland	Eidg. Forschungsanstalt für Betriebswirtschaft und Landtechnik. 1993. Op. cit.
Wheat	0.96	Australia	Wynen, E. 1994. Economics of organic farming in Australia. In N.H. Lampkin and S. Padel (eds). The Economics of Organic Farming: An International Perspective, CAB International, Wallingford, UK. p. 185–199.
Wheat	1.45	Australia	Leu, A. 2004. Organic agriculture can feed the world. Acres USA. January 2004.
Wheat, winter	1.14	Canada, Ontario	Stonehouse, P. 1991. Op. cit.
Wheat	1.12	Germany	Koepf, H.H. et al. 1976. Op. cit.
Wheat, spring	1.01	Germany	Raupp, J. 1996. Op. cit.
Wheat, spring	1.02	Germany	Raupp, J. 1996. Op. cit.
Wheat, Oats, Rye	1.00	Germany	Dabbert, S. 1990. Zur Optimalen Organisation Alternativer Landwirtschaftlicher Betriebe. Agrarwirtschaft Sonderheft 124. Verlag Alfred Strothe, Frankfurt.
Wheat	1.09	Israel	Levi, M. 1979. Principle of bio-organic agriculture. The Biosphere 8:30–35.
Wheat	0.68	New Zealand	Nguyen, M.L. and Haynes, R.J. 1995. Op. cit.
Wheat	0.88	Sweden, Jarna	Granstedt, A.G. and Kjellenberg, L. 1996. Quality investigations with the K-trial, Jarna, and other Scandinavian fertilization experiments. In J. Raupp (ed.). Quality of Plant Products Grown with Manure Fertilization. Vol. 9. Institute for Biodynamic Research. Darmstadt. p. 3–12.
Wheat	0.80	Sweden, Uppsala	Granstedt, A.G. and Kjellenberg, L. 1996. Op. cit.
Wheat	0.77	Switzerland	Eidg. Forschungsanstalt für Betriebswirtschaft und Landtechnik. 1993. Op. cit.
Wheat	0.86	Switzerland	Steinmann, R. 1983. Op. cit.
Wheat	0.87	Switzerland	Mäder, P., Fleißbach, A., Dubois, D., Gunst, L., Fried, P. and Niggli, U. 2002. Soil fertility and biodiversity in organic farming. Science 296:1694–1697.
Wheat	0.98	US, California	McGuire, A.M., Bryant, D.C., and Denison, R.F. 1998. Wheat yields, nitrogen uptake, and soil moisture following winter legume cover crop vs. fallow. Agronomy Journal 90:404–410.
Wheat	0.96	US, California	McGuire, A.M. et al. 1998. Op. cit.
Wheat	0.83	US, California	McGuire, A.M. et al. 1998. Op. cit.
Wheat	0.81	US, California	McGuire, A.M. et al. 1998. Op. cit.
Wheat	0.56	US, Michigan	Kellogg Biological Station Long Term Ecological Research, http://lter.kbs.msu.edu.
Wheat	0.55	US, Michigan	Kellogg Biological Station Long Term Ecological Research, http://lter.kbs.msu.edu.
Wheat	0.57	US, midwest	Lockeretz, W. et al. 1981. Op. cit.
Wheat	0.78	US, New York, Pennsylvania	Berardi, G.M. 1978. Organic and conventional wheat production: Examination of energy and economics. Agro-Ecosystems 4:367–376.
Wheat	1.05	US, Ohio	National Research Council. 1989. Op. cit.
Wheat	1.00	US, Pennsylvania	National Research Council. 1989. Op. cit.
Wheat	1.09	US, South Dakota	Smolik, J.D. et al. 1995. Op. cit.
Wheat	0.97	US, South Dakota, Michigan	Liebhardt, B. 2001. Op. cit.
Wheat	1.00	US, western corn belt	Roberts, K.J. et al. 1979. Op. cit.
Wheat	1.15	UK	Jenkinson, D.S., Bradbury, N.J., and Coleman, K. 1994. In R.A. Leigh and A.E. Johnston (eds). Long-term Experiments in Agricultural and Ecological Sciences. CAB International, Wallingford, UK. p. 117–138.
Wheat	0.68	UK	Trewavas, A. 2004. Op. cit.
Starchy roots			
Potatoes	0.85	Canada, Nova Scotia	Warman, P.R. and Havard, K.A. 1998. Op. cit.

Table A1. Continued.

Crop	Yield ratio	Location	Reference
Potatoes	1.18	Germany	Koepf, H.H. et al. 1976. Op. cit.
Potatoes	0.90	Germany	Raupp, J. 1996. Op. cit.
Potatoes	0.96	Germany	Raupp, J. 1996. Op. cit.
Potatoes	0.96	Germany	Raupp, J. 1996. Op. cit.
Potatoes	1.06	Germany	Raupp, J. 1996. Op. cit.
Potatoes	1.00	Israel	Levi, M. 1979. Op. cit.
Potatoes	0.86	Sweden	Dlouhy, J. 1981. Op. cit.
Potatoes	0.69	Sweden	Dlouhy, J. 1981. Op. cit.
Potatoes	0.82	Sweden, Jarna	Granstedt, A.G. and Kjellenberg, L. 1996. Op. cit.
Potatoes	0.81	Sweden, Uppsala	Granstedt, A.G. and Kjellenberg, L. 1996. Op. cit.
Potatoes	0.62	Switzerland	Mäder, P. et al. 2002. Op. cit.
Potatoes	0.74	Switzerland	Eidg. Forschungsanstalt für Betriebswirtschaft und Landtechnik. 1993. Op. cit.
Potatoes	1.03	Switzerland	Steinmann, R. 1983. Op. cit.
Sugars and sweeteners			
Sugar beet	1.02	Germany	Koepf, H.H. et al. 1976. Op. cit.
Sugar beet	0.99	Israel	Levi, M. 1979. Op. cit.
Legumes (Pulses)			
Beans, bush	0.83	Germany	Lindner, U. 1987. Alternativer Anbau–eine Alternative für den Erwerbsgemüsebau Gartenbauliche Versuchsberichte der Landwirtschaftkammer Rheinland 5:106–109.
Beans, dry	1.17	US, Maine	Eggert, F.M. 1983. Effect of soil management practices on yield and foliar nutrient concentration of dry beans, carrots and tomatoes. In W. Lockeretz (ed.). Environmentally Sound Agriculture. Praeger, New York. p. 247–259.
Beans, green	0.90	Canada, Ontario	Sellen, D. et al. 1993. Op. cit.
Beans, runner	0.65	Germany	Lindner, U. 1987. Op. cit.
Beans, winter	0.72	UK	Trewavas, A. 2004. Op. cit.
Peas	0.83	New Zealand	Nguyen, M.L. and Haynes, R.J. 1995. Op. cit.
Peas, dried	0.61	UK	Trewavas, A. 2004. Op. cit.
Oil crops			
Soybeans	0.94	US, 5 states	Liebhardt, B. 2001. Op. cit.
Soybeans	1.01	US, Iowa	Delate, K. and Cambardella, C.A. 2004. Op. cit.
Soybeans	0.95	US, midwest	Lockeretz, W. et al. 1981. Op. cit.
Soybeans	0.81	US, Minnesota	Porter, P. et al. 2003. Op. cit.
Soybeans	1.39	US, Ohio	National Research Council. 1989. Op. cit.
Soybeans	1.00	US, Pennsylvania	Hanson, J.C., Lichtenberg, E., and Peters, S.E. 1997. Organic versus conventional grain production in the mid-Atlantic: an economic and farming system overview. American Journal of Alternative Agriculture 12:2–9.
Soybeans	1.26	US, Pennsylvania	National Research Council. 1989. Op. cit.
Soybeans	0.97	US, Pennsylvania	Pimentel, D. et al. 2005. Op. cit.
Soybeans	0.88	US, Pennsylvania	Pimentel, D. et al. 2005. Op. cit.
Soybeans	1.00	US, South Dakota	Smolik, J.D. et al. 1995. Op. cit.
Soybeans	1.03	US, South Dakota	Smolik, J.D. et al. 1995. Op. cit.
Soybeans	0.77	US, South Dakota	Dobbs, T. and Smolik, J.D. 1996. Op. cit.
Soybeans	0.87	US, western corn belt	Roberts, K.J. et al. 1979. Op. cit.
Vegetables			
Beetroot	1.01	Germany	Raupp, J. 1996. Op. cit.
Beetroot	1.06	Germany	Raupp, J. 1996. Op. cit.
Beetroot	0.91	Germany	Lindner, U. 1987. Op. cit.
Cabbage	0.98	Canada, Nova Scotia	Warman, P.R. and Havard, K.A. 1997. Op. cit.
Cabbage	0.81	Canada, Ontario	Sellen, D. et al. 1993. Op. cit.
Cabbage	0.67	Germany	Lindner, U. 1987. Op. cit.
Carrots	1.06	Canada, Nova Scotia	Warman, P.R. and Havard, K.A. 1997. Yield, vitamin and mineral contents of organically and conventionally grown carrots and cabbage. Agriculture, Ecosystems and Environment 61:155–162.

Table A1. Continued.

Crop	Yield ratio	Location	Reference
Carrots	1.04	Germany	Raupp, J. 1996. Op. cit.
Carrots	1.08	Germany	Raupp, J. 1996. Op. cit.
Carrots	0.97	Israel	Levi, M. 1979. Op. cit.
Carrots	0.95	US, Maine	Eggert, F.M. 1983. Op. cit.
Cauliflower	0.64	Germany	Lindner, U. 1987. Op. cit.
Celeriac	0.96	Germany	Lindner, U. 1987. Op. cit.
Endive	0.80	Germany	Lindner, U. 1987. Op. cit.
Fennel	0.76	Germany	Lindner, U. 1987. Op. cit.
Kohlrabi	0.84	Germany	Lindner, U. 1987. Op. cit.
Leeks	0.92	Germany	Lindner, U. 1987. Op. cit.
Lettuce	0.76	Germany	Lindner, U. 1987. Op. cit.
Onions, Spanish	0.78	Canada, Ontario	Sellen, D. et al. 1993. Op. cit.
Savoy	0.83	Germany	Lindner, U. 1987. Op. cit.
Spinach	0.65	Germany	Lindner, U. 1987. Op. cit.
Tomatoes	0.55	Canada, Ontario	Sellen, D. et al. 1993. Op. cit.
Tomatoes	1.00	US, California	Liebhardt, B. 2001. Op. cit.
Tomatoes	0.83	US, California	Clark, M.S. et al. 1998. Op. cit.
Tomatoes	0.89	US, California	Clark, M.S. et al. 1998. Op. cit.
Tomatoes	0.97	US, California	Poudel, D.D. et al. 2002. Op. cit.
Tomatoes	1.00	US, California	Drinkwater, L.E. et al. 1995. Op. cit.
Tomatoes	1.04	US, Maine	Eggert, F.M. 1983. Op. cit.
Vegetables	0.68	Canada	Parsons, W. 2002. Organic fruit and vegetable production: Is it for you? Vista: Statistics Canada; Agriculture Division.
Vegetables	0.71	UK	Department for Environment, Food, and Rural Affairs (DEFRA). 2002. www.hdra.org.uk/pdfs/Conversion_report_2001-2002.pdf.
Vegetables, leafy	1.00	Japan	Xu, H.L., Wang, R., Xu, R.Y., Mridha, M.A.U., and Goyal, S. 2003. Yield and quality of leafy vegetables grown with organic fertilizations. Acta Horticulturae 627:25–33.
Fruits			
Apples	1.00	US, Washington	Reganold, J.P., Glover, J.D., Andrews, P.K., and Hinman, J.R. 2001. Sustainability of three apple production systems. Nature 410:926–930.
Fruits	0.91	Canada	Parsons, W. 2002. Op. cit.
Meat and offals			
Beef, bull	1.01	Germany	Lölau, S. and Zerger, U. 1989, 1991. Datenauswertung im Rahmen des Agrarkulturpreises der KLS-Stiftung. Munich (cited in Lampkin, N.H. and Padel, S. (eds). 1994. Op. cit.)
Beef, milk cows	1.07	Germany	Koepf, H.H. et al. 1976. Op. cit.
Beef	1.01	UK	Younie, D., Watson, C., Halliday, G., Armstrong, G., Slee, W., and Daw, M. 1990. Organic Beef in Practice. Scottish Agricultural College, Aberdeen.
Chicken, broiler	0.86	Italy	Castellini, C., Mugnai, C., and Dal Bosco, M. 2002. Effect of organic production system on broiler carcass and meat quality. Meat Science 60:219–225.
Lamb	0.86	Italy	Morbidini, L., Sarti, D.M., Pollidori, P., and Valigi, A. 1999. Carcass, meat and fat quality in Italian Merino derived lambs obtained with 'organic' farming systems. FAO-CIHEAM Network. http://ressources.ciheam.org/om/pdf/a46/01600108.pdf
Pork	1.11	Germany	Lölau, S. and Zerger, U. 1989, 1991. Op. cit.
Pork	0.98	Germany	Sundrum, A., Bütfering, L., Henning, M., and Hoppenbrock, K.H. 2000. Effects of on-farm diets for organic pig production on performance and carcass quality. Journal of Animal Science 78:1199–1205.
Pork	1.00	Sweden	Olsson, V., Andersson, K., Hansson, I., and Lundström, K. 2003. Differences in meat quality between organically and conventionally produced pigs. Meat Science 64:287–297.
Milk, excl. butter			
Milk	1.06	Australia	Dornom, H. and Tribe, D.E. 1976. Energetics of dairying in Gippsland. Search 7:431–433.

Table A1. Continued.

Crop	Yield ratio	Location	Reference
Milk	0.80	Canada, Quebec	Burgoyne, D. 1992. Analyse économique comparée de l'impact du niveau d'intensification, de l'utilisation d'intrants et de la production biologique sur la rentabilité des enterprises laitières au Québec. MSc thesis, FSAA, Université Laval, Quebec.
Milk	0.98	Denmark	Kristensen, T. and Kristensen, E.S. 1998. Analysis and simulation modelling of the production in Danish organic and conventional dairy herds. Livestock Production Science 54:55–65.
Milk	0.95	Denmark	Refsgaard, K., Halberg, N., and Kristensen, E.S. 1998. Energy utilization in crop and dairy production in organic and conventional livestock production systems. Agricultural Systems 57:599–630.
Milk	0.90	Germany	Winter, R. 1991. Economic questions of dairy production in ecological agriculture in northern Germany. In E. Boehncke and V. Molkenthin (eds). Alternatives in Animal Husbandry. Proceedings of the International Conference, July 1991. University of Kassel, Witzenhausen, Germany.
Milk	0.78	Germany	Haas, G., Wetterich, F., and Köpke, U. 2001. Comparing intensive, extensified and organic grassland farming in southern Germany by process life cycle assessment. Agriculture, Ecosystems and Environment 83:43–53.
Milk	1.29	Germany	Koepf, H.H. 1981. Op. cit.
Milk	0.78	Norway	Reksen, O., Tverdal, A., and Ropstad, E. 1999. A comparative study of reproductive performance in organic and conventional dairy husbandry. Journal of Dairy Science 82:2605–2610.
Milk	0.91	Sweden	Cederberg, C. and Mattsson, B. 2000. Life cycle assessment of milk production—a comparison of conventional and organic farming. Journal of Cleaner Production 8:49–60.
Milk	0.99	Switzerland	Eidg. Forschungsanstalt für Betriebswirtschaft und Landtechnik. 1993. Op. cit.
Milk	1.00	UK	Haggar, R. and Padel, S. 1996. Conversion to Organic Milk Production, Institute of Grassland and Environmental Research (IGER) Technical Review no. 4, Aberystwyth, UK.
Milk	0.91	UK	Houghton, M. and Poole, A.H. 1990. Organic Milk Production. Genus Information Unit Report 70. Genus Management, Wrexham, UK.
Milk	0.99	UK	Padel, S. 2000. Strategies of organic milk production. In M. Hovi and M. Bouilhol (eds). Human-animal Relationship: Stockmanship and Housing in Organic Livestock Systems, Proceedings of the 3rd NAHWOA (Network for Animal Health and Welfare in Organic Agriculture) Workshop. p. 121–135. Available at Web site: http://www.veeru.reading.ac.uk/organic/ProceedingsFINAL.pdf
Eggs			
Eggs	1.06	Germany	Lölau, S. and Zerger, U. 1989, 1991. Op. cit.

(B) Developing countries

Crop	Yield ratio	Location	Reference
Grains			
Barley	1.43	Peru	Altieri, M. 1999. Applying agroecology to enhance the productivity of peasant farming systems in Latin America. Environment, Development and Sustainability 1:197–217.
Maize	1.37	Argentina	Pretty, J. and Hine, R. 2001. Reducing food poverty with sustainable agriculture: a summary of new evidence. Centre for Environment and Society, Essex University. Available at Web site: http://www2.essex.ac.uk/ces/ResearchProgrammes/CESOccasionalPapers/SAFErepSUBHEADS.htm
Maize	1.30	Benin	Pretty, J. and Hine, R. 2001. Op. cit.
Maize	1.31	Brazil	Pretty, J. and Hine, R. 2001. Op. cit.
Maize	1.20	Brazil	Altieri, M. 2001. Applying agroecology to enhance the productivity of peasant farming systems in Latin America. Paper presented to Conference, Reducing Poverty through Sustainability, Saint James Palace, London.
Maize	3.50	Brazil	Altieri, M. 2001. Op. cit.

Table A1. Continued.

Crop	Yield ratio	Location	Reference
Maize	2.78	China	Pretty, J. and Hine, R. 2001. Op. cit.
Maize	1.38	China	Pretty, J. and Hine, R. 2001. Op. cit.
Maize	1.09	China	Pretty, J. and Hine, R. 2001. Op. cit.
Maize	1.71	Colombia	Pretty, J. and Hine, R. 2001. Op. cit.
Maize	3.71	Guatemala	Pretty, J. and Hine, R. 2001. Op. cit.
Maize	3.00	Honduras	Pretty, J. and Hine, R. 2001. Op. cit.
Maize	2.28	Honduras	Pretty, J. and Hine, R. 2001. Op. cit.
Maize	2.00	Kenya	Pretty, J. and Hine, R. 2001. Op. cit.
Maize	3.49	Kenya	Pretty, J. and Hine, R. 2001. Op. cit.
Maize	1.46	Kenya	Pretty, J. and Hine, R. 2001. Op. cit.
Maize	1.50	Malawi	Pretty, J. and Hine, R. 2001. Op. cit.
Maize	1.33	Nepal	Pretty, J. and Hine, R. 2001. Op. cit.
Maize	3.14	Nicaragua	Pretty, J. and Hine, R. 2001. Op. cit.
Maize	1.71	Niger	Pretty, J. and Hine, R. 2001. Op. cit.
Maize	2.22	Paraguay	Pretty, J. and Hine, R. 2001. Op. cit.
Maize	1.65	Peru	Altieri, M. 1999. Op. cit.
Maize	2.50	Peru	Altieri, M. 2001. Op. cit.
Maize	1.20	Philippines	Pretty, J. and Hine, R. 2001. Op. cit.
Maize	3.27	Philippines	Pretty, J. and Hine, R. 2001. Op. cit.
Maize	1.26	Sri Lanka	Scialabba, N. El-H. and Hattam, C. (eds). 2003. Op cit..
Maize	2.00	Tanzania	Pretty, J. and Hine, R. 2001. Op. cit.
Millet	1.73	Ethiopia	Pretty, J. and Hine, R. 2001. Op. cit.
Rice	1.08	Bangladesh	Pretty, J. and Hine, R. 2001. Op. cit.
Rice	1.12	China	Pretty, J. and Hine, R. 2001. Op. cit.
Rice	1.08	Indonesia	Pretty, J. and Hine, R. 2001. Op. cit.
Rice	1.00	Sri Lanka	Pretty, J. and Hine, R. 2001. Op. cit.
Rice	1.28	Sri Lanka	Pretty, J. and Hine, R. 2001. Op. cit.
Rice	1.09	Vietnam	Pretty, J. and Hine, R. 2001. Op. cit.
Rice, SRI	0.93	Bangladesh	Latif, M.A., Islam, M.R., Ali, M.Y., and Saleque, M.A. 2005. Validation of the system of rice intensification (SRI) in Bangladesh. Field Crops Research 93:281–292.
Rice, SRI	0.84	Bangladesh	Latif, M.A. et al. 2005. Op. cit.
Rice, SRI	1.17	Bangladesh	Latif, M.A. et al. 2005. Op. cit.
Rice, SRI	0.89	Bangladesh	Latif, M.A. et al. 2005. Op. cit.
Rice, SRI	1.18	Bangladesh	Latif, M.A. et al. 2005. Op. cit.
Rice, SRI	1.29	Madagascar	Barison, J. 2002. Evaluation of nutrient uptake and nutrient-use efficiency of SRI and conventional rice cultivation methods in Madagascar. In N. Uphoff, E.C.F. Fernandes, L.P. Yuan, J. Peng, S. Rafaralahy, and J. Rabenandrasana (eds). Assessments of the System of Rice Intensification (SRI): Proceedings of an International Conference, Sanya, China, CIIFAD, Ithaca, NY. p. 143–147.
Rice, SRI	1.20	Bangladesh	BRRI (http://ciifad.cornell.edu/sri/countries/bangladesh/bangrisrifnl.pdf), cited in McDonald, A.J., Hobbs, P.R., and Riha, S.J. 2005. Does the system of rice intensification outperform conventional best management? A synopsis of the empirical record. Field Crops Research 96:31–36.
Rice, SRI	1.22	China	Shengfu, A., Xiehui, W., Zhongjiong, X., Shixiu, X., Chengquan, L., and Yangchang, L. 2002. Assessment of using SRI with the super hybrid rice variety Liangyoupei 9. In N. Uphoff et al. (eds). Op. cit. p. 112–115.
Rice, SRI	1.19	India	MSSRF (http://ciifad.cornell.edu/sri/countries/india/), cited in McDonald, A.J. et al. 2005. Op. cit.
Rice, SRI	1.11	Laos	Welthungerhilfe (http://ciifad.cornell.edu/sri/countries/laos/laoritr102.pdf), cited in McDonald, A.J. et al. 2005. Op. cit.
Rice, SRI	1.10	Sri Lanka	Nissanka, S. and Bandara, T. 2004. Comparison of productivity of system of rice intensification and conventional rice farming systems in the dry-zone region of Sri Lanka. Fourth International Crop Science Congress (ICSC2004). Available at Web site: http://www.cropscience.org.au/icsc2004/poster/1/2/1177_nissankara.htm
Rice, SRI	1.09	China	Sheehy, J.E., Peng, S., Dobermann, A., Mitchell, P.L., Ferrer, A., Jianchang, Y., Zou, Y., Zhong, X., and Huang, J. 2004. Fantastic yields in the system of rice intensification: fact or fallacy? Field Crops Research 88:1–8.

Table A1. Continued.

Crop	Yield ratio	Location	Reference
Rice, SRI	1.09	Indonesia	Markarim, A.K., Balasubramanian, V., Zaini, Z., Syamsiah, I., Diratmadja, I.G.P.A., Arafah, H., Wardana, I.P., and Gani, A. 2002. System of rice intensification (SRI): Evaluation of seedling age and selected components. In B.A. Bouman, H. Hengsdijk, B. Hardy, P.S. Bindraban, T.P. Tuong, and J.K. Ladha (eds). Water-wise Rice Production, Proceedings of International Workshop on Water-Wise Rice Production, International Rice Research Institute. Los Banos, Phillipines, p. 356.
Rice, SRI	1.02	China	Qingquan, Y. 2002. The system of rice intensification and its use with hybrid rice varieties in China. In N. Uphoff et al. (eds). Op. cit. p. 109–111.
Rice, SRI	1.02	China	Shao-hua, W., Weixing, C., Dong, J., Tingbo, D., and Yan, Z. 2002. Physiological characteristics and high-yield techniques with SRI rice. In N. Uphoff et al. (eds). Op. cit. p. 116–124.
Rice, SRI	1.02	China	Shao-hua, W. et al. 2002. Op. cit.
Rice, SRI	1.02	Bangladesh	Duxbury, J.M., cited in McDonald, A.J. et al. 2005. Op. cit.
Rice, SRI	0.99	China	Sheehy, J.E. et al. 2004. Op. cit.
Rice, SRI	0.95	Nepal	Evans, C., Justice, S., and Shrestha, S. 2002. Experience with the system of rice intensification in Nepal. In N. Uphoff et al. (eds). Op. cit. p. 64–66.
Rice, SRI	0.95	China	Shao-hua, W. et al. 2002. Op. cit.
Rice, SRI	0.94	China	Shao-hua, W. et al. 2002. Op. cit.
Rice, SRI	0.93	China	Shao-hua, W. et al. 2002. Op. cit.
Rice, SRI	0.92	Bangladesh	Duxbury, J.M., cited in McDonald, A.J. et al. 2005. Op. cit.
Rice, SRI	0.91	China	Sheehy, J.E. et al. 2004. Op. cit.
Rice, SRI	0.90	Thailand	Gypmantasiri, P. 2002. Experience with the system of rice intensification in northern Thailand. In N. Uphoff et al. (eds). Op. cit. p. 75–79.
Rice, SRI	0.86	Laos	DED (http://ciifad.cornell.edu/sri/countries/laos/laoritr102.pdf)
Rice, SRI	0.83	Bangladesh	Duxbury, J.M., cited in McDonald, A.J. et al. 2005. Op. cit.
Rice, SRI	0.82	Bangladesh	Duxbury, J.M., cited in McDonald, A.J. et al. 2005. Op. cit.
Rice, SRI	0.73	Philippines	Rickman, J.F. 2004. Preliminary results: Rice production and the system of rice intensification. Available at Web site: http://ciifad.cornell.edu/sri/countries/philippines/irrieval.pdf
Rice, SRI	0.73	India	Annapurna farm (http://ciifad.cornell.edu/sri/countries/india/)
Rice, SRI	0.64	Thailand	Sooksa-nguan, T., Teaumroong, N., Boonkerd, N., Gypmantasiri, P., and Thies, J.E. 2004. Microbial community activity and structure associated with the system of rice intensification in northern Thailand. In: Soil Science Society of America, 68th Annual Meeting, Seattle, WA.
Rice, SRI	0.63	Laos	GTZ (http://ciifad.cornell.edu/sri/countries/laos/laoritr102.pdf)
Rice, SRI	0.62	Thailand	Gypmantasiri, P. 2002. Op. cit.
Rice, SRI	0.80	Bangladesh	Duxbury, J.M., cited in McDonald, A.J. et al. 2005. Op. cit.
Rice, SRI	0.75	Nepal	Duxbury, J.M., cited in McDonald, A.J. et al. 2005. Op. cit.
Rice, SRI	0.60	Thailand	Gypmantasiri, P. 2002. Op. cit.
Rice, SRI	0.45	Philippines	Rickman, J.F. 2004. Op. cit.
Rice, SRI	0.39	Laos	NRRP (http://ciifad.cornell.edu/sri/countries/laos/laoritr102.pdf)
Rice, SRI	1.29	Bangladesh	Uphoff, N. 2003. Higher yields with fewer external inputs? The system of rice intensification and potential contributions to agricultural sustainability. International Journal of Agricultural Sustainability 1:38–50.
Rice, SRI	1.78	Cambodia	Uphoff, N. 2003. Op. cit.
Rice, SRI	1.14	China	Uphoff, N. 2003. Op. cit.
Rice, SRI	1.58	Cuba	Uphoff, N. 2003. Op. cit.
Rice, SRI	3.09	Gambia	Uphoff, N. 2003. Op. cit.
Rice, SRI	1.48	Indonesia	Uphoff, N. 2003. Op. cit.
Rice, SRI	2.77	Madagascar	Uphoff, N. 2003. Op. cit.
Rice, SRI	2.95	Madagascar	Uphoff, N. 2003. Op. cit.
Rice, SRI	2.00	Philippines	Uphoff, N. 2003. Op. cit.
Rice, SRI	2.12	Sierra Leone	Uphoff, N. 2003. Op. cit.
Rice, SRI	2.17	Sri Lanka	Uphoff, N. 2003. Op. cit.
Rice, upland	2.80	India	Pretty, J. and Hine, R. 2001. Op. cit.
Rice, upland	1.87	India	Pretty, J. and Hine, R. 2001. Op. cit.

Table A1. Continued.

Crop	Yield ratio	Location	Reference
Rice, upland	3.40	Nepal	Pretty, J. and Hine, R. 2001. Op. cit.
Rice, upland	1.50	Nepal	Pretty, J. and Hine, R. 2001. Op. cit.
Rice, upland	1.23	Pakistan	Wai, O.K. 1995. Food, culture, trade and the environment in Asia. Ecology and farming (published by International Federation of Organic Agriculture Movements) 10:22–26.
Rice, upland	1.13	Philippines	Pretty, J. and Hine, R. 2001. Op. cit.
Sorghum	1.65	India	Pretty, J. and Hine, R. 2001. Op. cit.
Sorghum/Millet	2.10	Burkina Faso	Pretty, J. and Hine, R. 2001. Op. cit.
Sorghum/Millet	3.50	India	Pretty, J. and Hine, R. 2001. Op. cit.
Sorghum/Millet	1.76	India	Pretty, J. and Hine, R. 2001. Op. cit.
Sorghum/Millet	2.12	India	Pretty, J. and Hine, R. 2001. Op. cit.
Sorghum/Millet	2.25	India	Pretty, J. and Hine, R. 2001. Op. cit.
Sorghum/Millet	5.67	Mali	Pretty, J. and Hine, R. 2001. Op. cit.
Sorghum/Millet	1.71	Niger	Pretty, J. and Hine, R. 2001. Op. cit.
Sorghum/Millet	2.35	Senegal	Pretty, J. and Hine, R. 2001. Op. cit.
Sorghum/Teff	1.50	Ethiopia	Pretty, J. and Hine, R. 2001. Op. cit.
Wheat	1.17	China	Pretty, J. and Hine, R. 2001. Op. cit.
Wheat	1.17	Pakistan	Pretty, J. and Hine, R. 2001. Op. cit.
Wheat	1.25	Pakistan	Wai, O.K. 1995. Op. cit.
Starchy roots			
Cassava	1.30	Cuba	Ruiz, L. 1993. Factores que condicionan la eficiencia de las micorrizas arbusculares, como alternativa para la fertilización de las raíces y tubérculos tropicales. Dissertation, Agricultural University of Havana (UNAH), Havana.
Cassava	1.75	Ghana	Pretty, J. and Hine, R. 2001. Op. cit.
Potatoes	1.50	Bolivia	Pretty, J. and Hine, R. 2001. Op. cit.
Potatoes	3.50	Bolivia	Pretty, J. and Hine, R. 2001. Op. cit.
Potatoes	1.43	Peru	Altieri, M. 1999. Op. cit.
Potatoes	3.08	Peru	Pretty, J. and Hine, R. 2001. Op. cit.
Potatoes	4.40	Peru	Pretty, J. and Hine, R. 2001. Op. cit.
Potatoes	1.60	Peru	Pretty, J. and Hine, R. 2001. Op. cit.
Sweet Potato	5.83	Ethiopia	Pretty, J. and Hine, R. 2001. Op. cit.
Sweet Potato	3.78	Indonesia	Pretty, J. and Hine, R. 2001. Op. cit.
Sweet Potato	1.50	Indonesia	Pretty, J. and Hine, R. 2001. Op. cit.
Legumes (pulses)			
Beans	5.67	Honduras	Bunch, R. 1999. More productivity with fewer external inputs: Central American case studies of agroecological development and their broader implications. Environment, Development and Sustainability 1:219–233.
Beans	2.32	Honduras	Pretty, J. and Hine, R. 2001. Op. cit.
Oil crops			
Peanut	1.64	Senegal	Altieri, M. and Uphoff, N. 2001. Alternatives to conventional modern agriculture for meeting food needs in the next century. Cornell International Institute for Food, Agriculture, and Development. Available at Web site: http://ciifad.cornell.edu/documents/bellagioenglish.pdf.
Soybean	1.65	Brazil	Pretty, J. and Hine, R. 2001. Op. cit.
Vegetables			
Cabbage	1.21	Philippines	Pretty, J. and Hine, R. 2001. Op. cit.
Vegetables	1.39	Bangladesh	Pretty, J. and Hine, R. 2001. Op. cit.
Vegetables	4.15	Chile	Pretty, J. and Hine, R. 2001. Op. cit.
Vegetables	2.00	Kenya	Pretty, J. and Hine, R. 2001. Op. cit.
Vegetables	1.48	Malawi	Pretty, J. and Hine, R. 2001. Op. cit.
Vegetables	2.00	Zimbabwe	Pretty, J. and Hine, R. 2001. Op. cit.
Fruits			
Fruit	1.25	Cuba	Treto, E., M. García, R.M. Viera, J.M. Febles. 2002. Advances in organic soil management. In F. Funes, L. García, M. Bourque, N. Pérez, and P. Rosset (eds). Sustainable Agriculture and Resistance: Transforming Food Production in Cuba. Food First Books, Oakland, CA. p. 164–189.

Table A1. Continued.

Crop	Yield ratio	Location	Reference
Banana/Plantain	1.90	Uganda	Pretty, J. and Hine, R. 2001. Op. cit.
Banana/Plantain	4.00	Uganda	Pretty, J. and Hine, R. 2001. Op. cit.
Citrus	2.75	Pakistan	Pretty, J. and Hine, R. 2001. Op. cit.
Mango	2.75	Pakistan	Pretty, J. and Hine, R. 2001. Op. cit.
Milk, excl. butter			
Milk	4.00	Cameroon	Pretty, J. and Hine, R. 2001. Op. cit.
Milk	1.60	India	Pretty, J. and Hine, R. 2001. Op. cit.
Milk	2.57	Tanzania	Pretty, J. and Hine, R. 2001. Op. cit.
Milk	4.00	Tanzania	Pretty, J. and Hine, R. 2001. Op. cit.
Milk	1.30	Uganda	Pretty, J. and Hine, R. 2001. Op. cit.

Appendix 2: Nitrogen from Cover Crops

Table A2. Data and sources for nitrogen availability from cover crops; the country where the study occurred is listed when it is known. Multiple entries from the same source represent data for different plant species or varieties. Values with asterisk (*) were calculated based on 66% of the N fixed by a cover crop becoming available for plant uptake during the growing season following the cover crop[34]. The other values are the 'fertilizer-replacement value,' determined as the amount of N fertilizer needed to achieve yields equivalent to those obtained using N from cover crops. Values from studies in the US were the basis for calculating the N available from cover crops for the United States in Table 4.

kg N ha^{-1}	Country	Reference
Temperate ($n = 33$)		
95.0	Canada	Odhiambo, J.J.O. and Bomke, A.A. 2001. Grass legume cover crop effects on dry matter and nitrogen 'Crimson Clover' accumulation. Agronomy Journal 93:299–307.
95.0	US	Balkcom, K.S. and Reeves, D.W. 2005. Sunn-hemp utilized as a legume cover crop for corn production. Agronomy Journal 97:26–31.
82.0	US	Cline, G.R. and Silvernail, A.F. 2002. Effects of cover crops, nitrogen, and tillage on sweet corn. HortTechnology 12:118–125.
94.0	US	Decker, A.M., Holderbaum, J.F., Mulford, R.F., Meisinger, J.J., and Vough, L.R. 1987. Fall-seeded legume nitrogen contributions to no-till corn production. In J.F. Power (ed.). Role of Legumes in Conservation Tillage System: Proceedings of a national conference, University of Georgia, Athens, April 27–29. Soil Conservation Society of America. p. 21–22.
56.0	US	Drinkwater, L.E., Wagoner, P., and Sarrantonio, M. 1998. Legume-based cropping systems have reduced carbon and nitrogen losses. Nature 396:262–265.
95.0	US	Ebelhar, S.A., Frye, W.W., and Belebins, R.L. 1984. Nitrogen From legume cover crops for no-tillage corn. Agronomy Journal 76:51–55.
104.0	US	Groffman, P.M., Hendrix, P.F., and Crossley Jr, D.A. 1987. Nitrogen cycling in conventional and no-tillage agroecosystems with inorganic fertilizer or legume nitrogen inputs. Plant and Soil 97:325–332.
91.0	US	Hargrove, W.L. 1986. Winter legumes as a nitrogen source for no-till grain sorghum. Agronomy Journal 78:70–74.
77.0	US	Herbek, J.H., Frye, W.W., and Blevins, R.L. 1987. Nitrogen from legume cover crops for no-till corn and grain sorghum. In J.F. Power (ed.). Op. cit., p. 51–52.
99.7	US	Holderbaum, J.F., Decker, A.M., Mulford, F.R., Meisinger, J.J., and Vough, L.R. 1987. Forage contributions of winter legume cover crops in no-till corn production. In J.F. Power (ed.). Op. cit., p. 98–99.
105.6	US	Hoyt, G.D. 1987. Legumes as a green manure in conservation tillage. In J.F. Power (ed). Op. cit., p. 96–97.
100.0	US	Hoyt, G.D. and Hargrove, W.L. 1986. Legume cover crops for improving crop and soil management in the southern United States. HortScience 21:397–492.
84.0	US	Leidner, M.B. 1987. Crimson clover and corn: A conservation tillage system that works in Georgia's Coastal Plain. In J.F. Power (ed.). Op. cit., p. 103–104.
62.0	US	Ngalla, C.F. and Eckert, D.J. 1987. Wheat-red clover interseeding as a nitrogen source for no-till corn. In J.F. Power (ed.), Op. cit., p. 47–48.

Table A2. Continued.

kg N ha^{-1}	Country	Reference
79.0	US	Oyer, L.J. and Touchton, J.T. 1987. Nitrogen fertilizer requirements for corn as affected by legume cropping systems and rotations. In J.F. Power (ed.). Op. cit., p. 44–45.
84.0	US	Pettygrove, G.S. and Williams, J.F. 1997. Nitrogen-fixing cover crops for California rice production. University of California Davis Rice Project Web site. http://agronomy.ucdavis.edu/ucce/index.htm.
60.0	US	Pettygrove, G.S. and Williams, J.F. 1997. Nitrogen-fixing cover crops for California rice production. University of California Davis Rice Project Web site. http://agronomy.ucdavis.edu/ucce/index.htm.
40.0	US	Pettygrove, G.S. and Williams, J.F. 1997. Nitrogen-fixing cover crops for California rice production. University of California Davis Rice Project Web site. http://agronomy.ucdavis.edu/ucce/index.htm.
77.8	US	Poudel, D.D., Horwath, W.R., Lanini, W.T., Temple, S.R., and van Bruggen, A.H.C. 2002. Comparison of soil N availability and leaching potential, crop yields and weeds in organic, low-input and conventional farming systems in northern California. Agriculture, Ecosystems and Environment 90:125–137.
99.7	US	Poudel, D.D. et al. 2002. Op. cit.
17.8	US	Reddy, K.C., Soffes, A.R., and Prine, G.M. 1986. Tropical legumes for green manure. I. Nitrogen production and the effects on succeeding crop yields. Agronomy Journal 78:1–4.
92.4	US	Reddy, K.C. et al. 1986. Op. cit.
94.6	US	Reddy, K.C. et al. 1986. Op. cit.
107.8	US	Reddy, K.C. et al. 1986. Op. cit.
110.0	US	Reddy, K.C. et al. 1986. Op. cit.
125.4	US	Reddy, K.C. et al. 1986. Op. cit.
136.4	US	Reddy, K.C. et al. 1986. Op. cit.
101.6	US	Sainj, U.M., Singh, B.P., and Whitehead, W.F. 1998. Cover crop root distribution and its effects on soil nitrogen cycling. Agronomy Journal 90:511–518.
78.0	US	Schmidt, W.H., Myers, D., and Van Keuren, R.W. 1974. Value of legumes for plowdown nitrogen. Agronomy Tip Misc-4. Ohio Cooperative Extension Service, Columbus, Ohio.
231.0	US	Schulz, S., Keatinge, J.D.H., and Wells, G.J. 1999. Productivity and residual effects of legumes in rice-based cropping systems in a warm-temperate environment. II. Residual effects on rice. Field Crops Research 61:37–49.
171.6	US	Stivers, L.J., Shennan, C., Jackson, L.E., Groddy, K., Griffin, C.J., and Miller, P.R. 1993. Winter cover cropping in vegetable production systems in California. In M.G. Paoletti, W. Foissner, and D. Coleman (eds). Soil Biota Nutrient Cycling and Farming Systems. Lewis Publishers, Boca Raton, FL, p. 227–240.
68.0	US	Touchton, J.T., Rickerl, D.H., Walker, R.H., and Snipes, C.E. 1984. Winter legumes as nitrogen source for no-tillage cotton. Soil and Tillage Research 4:391–401.
123.0	US	Tyler, D.D., Duck, B.N., Graveel, J.G., and Bowen, J.F. 1987. Estimating response curves of legume nitrogen contribution to no-till corn. In J.F. Power (ed.). Op. cit., p. 50–51.
95.1		Average for temperate studies ($n = 33$)
Tropical ($n = 43$)		
16.5		Peoples, M.B., Herridge, D.F., and Ladha, J.K. 1995. Biological nitrogen fixation: an efficient source of nitrogen for sustainable agricultural production? Plant and Soil 174:3–28.
52.1		Peoples, M.B. et al. 1995. Op. cit.
66.7		Peoples, M.B. et al. 1995. Op. cit.
88.1		Peoples, M.B. et al. 1995. Op. cit.
99.0		Peoples, M.B. et al. 1995. Op. cit.
101.3		Peoples, M.B. et al. 1995. Op. cit.
130.0		Peoples, M.B. et al. 1995. Op. cit.
141.2		Peoples, M.B. et al. 1995. Op. cit.
176.2		Rinaudo, G., Dreyfus, B., and Dommergues, Y. 1983. *Sesbania rostrata* green manure and the nitrogen content of rice crop and soil. Soil Biology and Biochemistry 15: 111–113.
85.3	Brazil	Ambrosano, E.J. et al. 2005. Utilization of nitrogen from green manure and mineral fertilizer by sugarcane. Sci. Agric. (Piracicaba, Brazil) 62:534–542.
55.0	Colombia	Cobo, J.G., Barrios, E., Kass, D.C.L., and Thomas, R.J. 2002. Decomposition and nutrient release by green manures in a tropical hillside agroecosystem. Plant and Soil 240:331–342.
59.3	Colombia	Cobo, J.G. et al. 2002. Op. cit.
60.1	Colombia	Cobo, J.G. et al. 2002. Op. cit.
72.4	Colombia	Cobo, J.G. et al. 2002. Op. cit.
76.4	Colombia	Cobo, J.G. et al. 2002. Op. cit.

Table A2. Continued.

kg N ha^{-1}	Country	Reference
76.5	Colombia	Cobo, J.G. et al. 2002. Op. cit.
85.7	Colombia	Cobo, J.G. et al. 2002. Op. cit.
86.4	Colombia	Cobo, J.G. et al. 2002. Op. cit.
95.4	Colombia	Cobo, J.G. et al. 2002. Op. cit.
94.4	Cuba, Brazil	Ramos, M.G., Villatoro, M.A.A., Urquiaga, S., Alves, B.J.R., and Boddey, R.M. 2001. Quantification of the contribution of biological nitrogen fixation to tropical green manure crops and the residual benefit to a subsequent maize crop using ^{15}N-isotope techniques. Journal of Biotechnology 91:105–115.
56.1	India	Becker, M., Ladha, J.K., and Ali, M. 1995. Green manure technology: potential usage and limitations. A case study for lowland rice. Plant and Soil 174:181–194.
78.0	India	Ghai, S.K., Rao, D.L.N., and Batra, L. 1988. Nitrogen contribution to wetland rice by green manuring with *Sesbania* spp. in an alkaline soil. Biology and Fertility of Soils 6:22–25.
122.0	India	Ghai, S.K. et al. 1988. Op. cit.
104.3	India	Rao, D.L.N. and Gill, H.S. 1993. Nitrogen fixation, biomass production, and nutrient uptake by annual *Sesbania* species in an alkaline soil. Biology and Fertility of Soils 15:73–78.
75.9	Nigeria	Iberwiro, B., Sanginga, N., Vanlauwe, B., and Merckx, R. 2000. Evaluation of symbiotic dinitrogen inputs of herbaceous legumes into tropical cover-crop systems. Biology and Fertility of Soils 32:234–242.
64.4	Nigeria	Mulongoy, K. 1986. Microbial biomass and maize nitrogen uptake under a *Psophocarpus palustris* live-mulch grown on a tropical alfisol. Soil Biology and Biochemistry 18:395–398.
107.2	Philippines	George, T., Ladha, J.K., Garrity, D.P., and Torres, R.O. 1995. Nitrogen dynamics of grain legume-weedy fallow-flooded rice sequences in the tropics. Agronomy Journal 87:1–6.
101.3	Philippines	Pareek, R.K., Ladha, J.K., and Wantanabe, I. 1990. Estimating N_2 fixation by *Sesbania rostrata* and *S. cannabina* in lowland rice soil by the ^{15}N dilution method. Biology Fertility of Soils 10:77–88.
29.7	Philippines	Thonnissen, C., Midmore, D.J., Ladha, J.K., Olk, D.C., and Schmidhalter, U. 2000. Legume decomposition and nitrogen release when applied as green manures to tropical vegetable production systems. Agronomy Journal 92:253–260.
82.5	Philippines	Thonnissen, C. et al. 2000. Op. cit.
60.0	Philippines	Torres, R.O., Pareek, R.P., Ladha, J.K., and Garrity, D.P. 1995. Stem-nodulating legumes as relay-cropped or intercropped green manures for lowland rice. Field Crops Research 42:39–47.
423.0	Senegal	Alazard, D. and Becker, M. 1987. *Aeschynomene* as green manure for rice. Plant and Soil 101:141–143.
532.0	Senegal	Alazard, D. and Becker, M. 1987. Op. cit.
82.5	South Asia	Ladha, J.K., Pareek, R.P., and Becker, M. 1992. Stem-nodulating legume-*Rhizobium* symbiosis and its agronomic use in lowland rice. Advances in Soil Science 2:147–192.
174.2	South Asia	Ladha, J.K. et al. 1992. Op. cit.
145.2	South Asia	Ladha, J.K., Kundu, D.K., Coppenolle, M.G.A., Peoples, M.B., Carangal, V.R., and Dart, P.J. 1996. Legume productivity and soil nitrogen dynamics in lowland rice-based cropping systems. Soil Science Society of America Journal 6:183–192.
139.3	South Asia	Ladha, J.K. et al. 1996. Op. cit.
139.3	South Asia	Ladha, J.K. et al. 1996. Op. cit.
60.7	Sri Lanka	Palm, O., Weerakoon, W.L., de Silva, M.A.P., and Rosswall, T. 1988. Nitrogen mineralization of *Sesbania sesban* used as green manure for lowland rice in Sri Lanka. Plant and Soil 108:201–209.
110.6	Syria	Sultan, K., Ginntzburger, G., Obaton, M., Robin, C., Touchane, H., and Guckert, A. 2001. Growth and nitrogen fixation of annual *Medicago-Rhizobium* associations during winter in Mediterranean region. European Journal of Agronomy 15:221–229.
103.6	US	Rotar, P.P. and Joy, R.J. 1983. 'Tropic Sun' sunn hemp *Crotalaria juncea* L. Research Series, 36. Hawaiian Institute of Tropical Agriculture and Human Resources, University of Hawaii, Honolulu.
95.0	Uganda	Wortmann, C.S., McIntyre, B.D., and Kaizzi, C.K. 2002. Annual soil improving legumes: agronomic effectiveness, nutrient uptake, nitrogen fixation and water use. Field Crops Research 68:75–83.
66.0	West Africa	Carsky, R.J., Jagtap, S., Tian, G., Sanginga, N., and Vanlauwe, B. 1998. Maintenance of soil organic matter and nitrogen supply in the moist savanna zone of West Africa. In R. Lal (ed). Soil and Agricultural Sustainability. Sleeping Bear Press, Chelsea, MI.
108.6		Average for tropical studies ($n = 43$)
102.8		Average for all studies ($n = 76$)

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Ecological agriculture: Principles, practices, and constraints[1]

Fred Magdoff*

Department of Plant and Soil Science, University of Vermont, Burlington, VT 05401, USA.
*Corresponding author: fmagdoff@uvm.edu

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Abstract

The practice of ecological agriculture involves building the strengths of natural ecosystems into agroecosystems, purposely disturbed to produce food and fiber. The overall strategies include using practices that (a) grow healthy plants with good defense capabilities, (b) stressing pests, and (c) enhancing populations of beneficial organisms. These are accomplished by enhanced habitat management both above ground and in the soil. Many of the practices that contribute to the overall strategies are well known—such as intensive use of cover crops or reduced tillage. Reasons for why they have not been more widely used are discussed. The special challenges facing ecological agriculture in the poor countries of the Third World are also discussed. Re-engaging national governments in the active support of their agriculture and addressing the structural inequalities (including access to land) are essential to overcome the many problems facing farmers in the poor countries.

Key words: ecological agriculture, agroecology, soil management, crop management, farm subsidies, Third World agriculture

Why Ecological Agriculture?

It is acknowledged by most observers that there are currently plentiful supplies of food produced in the US and around the world—certainly sufficient so that no person should go hungry or be in a position of food insecurity. On the other hand, about half the people in the world are malnourished—3 billion people. In the US, according to USDA, in 2004 '... 38.2 million people lived in food-insecure households, including 13.9 million children. Of these individuals, 7.4 million adults and 3.3 million children lived in households where someone experienced hunger during the year.'[1] And a few years ago a *New York Times* article had a story with the following headline 'Poor in India Starve as Surplus Wheat Rots.'[2] As a *Wall Street Journal* headline put it in 2004 'Want Amid Plenty, An Indian Paradox: Bumper Harvests and Rising Hunger.'[3]

So, the current system of production can be considered, in one important way to be quite a success story—there is a lot of food produced. And on the other hand, many people here and around the world are hungry and malnourished. In addition, the ecological and sociological problems of contemporary conventional agriculture are in the news almost daily. Water pollution from nitrogen and phosphorus and pathogens results in health hazards or algal blooms. Some of these effects are local, others are regional (pollution of Lake Champlain or the Chesapeake Bay), and some, such as the problems caused by nitrates entering the Gulf of Mexico, are truly continental in scope. Other environmental problems include accelerated soil erosion by wind and/or water, pesticides in groundwater and on food, the pesticide 'treadmill' caused by development of pest resistance to pesticides, routine use of antibiotics for animals leading to antibiotic-resistant strains of organisms, disease organisms contaminating meat and produce, pesticide contamination of farm workers, and so on. A good part of the nutrient pollution from agriculture is caused by a geographic separation between animal production facilities (consisting now mainly of large buildings and feedlots) and where the animal feeds are produced. This necessitates the use of large quantities of commercial mined and processed potash and phosphate fertilizers as well as synthetic nitrogen fertilizers on the crop farms at the same time as nutrients accumulate as manure on the animal farms. Additionally, in the poor countries of the Third World, an over-reliance on grain crop monocultures and loss of crop diversity in the aftermath of the 'green revolution' has resulted in a loss of well-balanced diets.

[1] Modified from the keynote address to the conference 'Sustainability in the Balance: Juggling Environmental Health, Economic Profitability and Social Equity in the Global Food System', Friedman School of Nutrition Science and Policy, Tufts University, 11 April, 2006.

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The development of factory farms and the physical separation of most of the animals from the land on which their feed grows are of relatively recent origin, developing especially over the past 25–50 years[4,5]. Of longer duration, going back well over a century, has been the wide separation between where people live and where their food is produced. This causes both wasted energy for transportation of food as well as excess nutrient accumulation in and around urban areas. This issue, still very much with us today in the problems of treating and disposing of massive quantities of urban wastes, created some concern in the 19th century, as indicated by Karl Marx's comments:

> Capitalist production, by collecting the population in great centres, and causing an ever-increasing preponderance of town population, on the one hand concentrates the historical motive power of society; on the other hand, it disturbs the circulation of matter between man and the soil, i.e., prevents the return to the soil of its elements consumed by man in the form of food and clothing; it therefore violates the conditions necessary to lasting fertility of the soil. By this action it destroys at the same time the health of the town labourer and the intellectual life of the rural labourer.[6]

Another critical issue is the extreme dependence on fossil fuels in conventional agriculture and the entire food system. Fuel is not only used to produce and power the large-scale equipment now used in agriculture—the tractors and combines and trucks for transportation. It is also used for other purposes such as drying grain and for production of agrichemicals. Although pesticide production is costly in energy terms, one of the most energy costly agrichemicals is the production, distribution, and application of nitrogen fertilizers. The two nitrogen atoms of the N_2 molecule, so abundant in our atmosphere (78%), are held together by a triple bond that takes high temperature, pressure, energy, and catalysts, to convert to ammonia—the first product of Haber–Bosch process and the starting point for all other commercial N fertilizers.

The opening up of forests and grasslands for intensive agricultural production has caused, and continues to cause, a rapid decomposition (oxidation) of soil organic matter, leading to substantial releases of carbon dioxide (CO_2) into the atmosphere. There is over three times more carbon stored in soils than is in the atmosphere as CO_2. Thus, release of CO_2 from soils through oxidation of organic matter is of fairly large magnitude, while at the same time the soils are becoming less healthy because of the loss of organic matter (see estimates of historical CO_2 releases[7]).

Conventional farmers have been forced to become larger and highly mechanized—and, therefore, there are fewer of them—because of consolidation in the input and output (purchasing, processing and distribution) industries and low prices for their products. There are now few places to purchase needed inputs or wholesale markets to sell agricultural commodities. Farmers producing undifferentiated commodities must take advantage of all the physical and financial economies of scale in order to reduce their costs of production. In Iowa nowadays it takes about 1500 acres to make a living following conventional agriculture practices. This decrease in farm numbers and in agribusinesses that served the smaller farms has led to the decline and death of many rural communities. And the system continues along its 'merry' way in the US only with massive government subsidies—in 2001 an astonishing 47% of farm income came from government subsidies.[8]

Encouraged by agribusiness, agricultural science has contributed to the conventional system, with all its negative environmental and social effects. It has done so by taking a reductionist approach, where each issue that develops is viewed as an individual problem that needs to be addressed in isolation from all others. If soil fertility is low, just add fertilizers. If there is a pest outbreak (weed, insect, disease), then apply a pesticide. If the soil is compact, just use a subsoiler to relieve compaction. All issues are dealt with using a therapeutic approach. There is a 'problem' that needs some intervention, or therapy, to solve it. But what if these 'problems' are better viewed as symptoms of a deeper underlying and mostly hidden problem? What if these are caused by a poorly managed agricultural ecosystem?

Principles of Ecological Agriculture

The term ecological agriculture used in this essay is similar to agroecology in that it applies ecological principles and approaches to agricultural ecosystems. While not excluding organic agriculture, it is a broader concept that may be closer to 'sustainable' agriculture. Ecology is the 'missing science' in traditional agricultural education and research. Undergraduate and graduate agriculture students have until very recently studied basic sciences such as biology, chemistry and physics, but not ecology. In addition, the various agricultural disciplines have even been fragmented to sub-disciplines. No wonder the reductionist approach has been the norm. In going about the work of agriculture we purposefully disturb natural ecosystems (or formerly natural ecosystems) for the purpose of producing food and fiber crops and animal products of various kinds. These agroecosystems can be approached as any other ecosystem. An ecological approach to agriculture involves designing the strengths of natural ecosystem into agroecosystems. First we will discuss the strengths of natural ecosystems and then discuss how to develop these strengths in the context of farm fields and farms.

Strengths of natural ecosystems

Natural ecosystems exhibit certain strengths or characteristics. These include the following:

- **Efficiency.** Efficient energy flows are characteristic of natural systems. The sun's energy captured by green

plants is then used by many organisms, as fungi and bacteria decompose organic residues and are then fed upon by other organisms, which are themselves fed upon by others higher up the foodweb. Natural ecosystems also tend to be efficient in capturing and using rainfall and in mobilizing and cycling nutrients. This helps to keep the ecosystem from 'running down' through the excessive loss of nutrients and at the same time helps maintain the quality of the groundwater and surface waters. Precipitation tends to enter the porous soil, rather than runoff, providing water to plants as well as recharge to ground water, slowly releasing water to streams and rivers.

- **Diversity.** A great biological diversity, both above ground and in the soil, characterizes many natural ecosystems in temperate and tropical regions. This provides checks and balances, nutrient availability to plants, checks on disease outbreaks, etc. For example, competition for resources and specific antagonisms (such as antibiotic production) from the multitude of soil organisms usually keep soilborne plant diseases from severely damaging a natural grassland or forest.
- **Self-sufficiency.** A consequence of efficiency and diversity is that natural terrestrial ecosystems are self-sufficient—requiring only inputs of sunlight and rainfall.
- **Self-regulation.** Because of the great diversity of organisms, outbreaks (or huge population increases) of diseases or insects that severely damage plants or animals are uncommon. In addition, plants have a number of defense mechanisms that help protect them from attack.
- **Resiliency.** Disturbances occur in all ecosystems—natural or not. The stronger ones are more resistant to disturbances[9] and are able to bounce back quicker.

Building characteristics of strong ecosystems into agroecosystems

We need to learn to design farms, farming systems and landscapes to take advantage of the inherent strengths of natural systems, using minimal amounts of external interventions (inputs). Ideally, we would like to have agroecosystems that are productive but without the many negative 'externalities'—or unwanted side effects—of conventional agriculture. We would like agricultural ecosystems to demonstrate characteristics of strong ecosystems—efficiency, diversity, self-sufficiency, self-regulation and resilience. The only way to really come close to reaching these goals is to view farms and fields as systems and approach them as such. This will not necessarily eliminate all the problems associated with contemporary conventional agriculture but should go a long way to alleviating many of them. And we must remember, of course, that ecologically managed agricultural ecosystems, while mimicking strong natural ecosystems, are still purposefully disturbed systems that will not look or function the same as natural systems.

Agricultural fields and their surroundings. There is a three-step overall strategy to the production of crops relying heavily on ecological principles. Firstly, do everything reasonably possible to build internal strengths into the agricultural ecosystem. This aims at preventing 'problems' instead of dealing with them once they have appeared. Secondly, use routine ecologically sound practices during the season to keep plants healthy. Thirdly, if an unanticipated problem arises, use the most benign reactive (therapeutic) means possible to deal with it. Let us deal with each of these individually.

A. Building internal strengths into the system is usually done during the off-season through the time the crops are planted (see Fig. 1). *The overall goals are to create soil and above-ground conditions that promote the growth of healthy plants, to stress pests, and to promote beneficial organisms.* This can be viewed at as 'habitat management and conservation' to promote sufficient biological diversity and conditions for healthy growth of plants—above and below ground, in space (for example, field boundary management) and in time (cover crops, rotations). This is the heart of the matter, and for this reason we will discuss it in greater depth than the other two overall strategies. Although Fig. 1 and the discussion below divides strategies into 'above ground' and 'below ground' this is an artificial distinction. Many practices may have profound effects both above and below the soil surface.

Building strengths above ground

- *Select crops and varieties resistant to local pests (in addition to other qualities such as yield, taste, etc.)*
- *Use appropriate planting densities (and companion crops)*
- *Plant perimeter (trap) crops that are more attractive to a particular pest than the economic crop(s) growing in the middle of the field and can intercept incoming insects.*
- *Create field boundaries and zones within fields that are attractive to beneficial insects.* This usually involves planting a mix of flowering plants around or inside fields to provide shelter and food for beneficials.
- *Use cover crops routinely to provide multiple benefits such as habitat for beneficial insects, adding N and organic matter to soil, reducing erosion and enhancing water infiltration into the soil, retaining nutrients in soil, (and much more).* It is possible to supply all of the nitrogen to succeeding crops by growing a vigorous winter legume cover crop such as crimson clover in the south and hairy vetch in the north.
- *Use rotations that are complex, involve plants of different families and, if at all possible, include sod crops such as grass/clover hay that remain without soil disturbance for a number of years.*
- *Reducing tillage is an important part of an ecological approach to agriculture.* Tillage buries residues, leaving the soil bare and more susceptible to the erosive effects of rainfall, and at the same time breaks up natural soil aggregates that help infiltration, storage and drainage of precipitation. (The use of practices that reduce erosion is critical to sustaining soil productivity[10].)

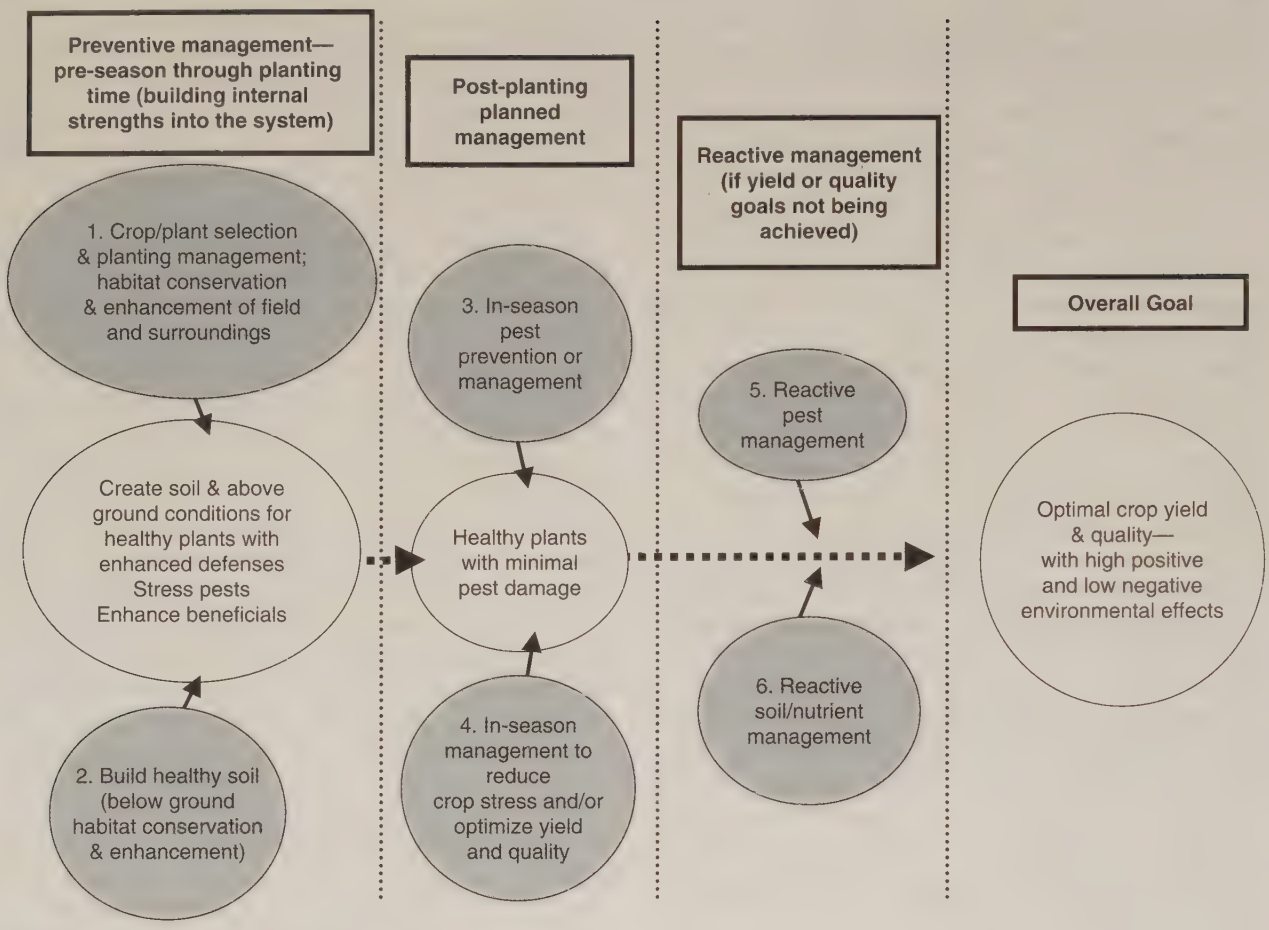
Preventive management—pre-season through planting time (building internal strengths into the system)
Post-planting planned management
Reactive management (if yield or quality goals not being achieved)
Overall Goal
1. Crop/plant selection & planting management; habitat conservation & enhancement of field and surroundings
3. In-season pest prevention or management
5. Reactive pest management
Optimal crop yield & quality—with high positive and low negative environmental effects
Create soil & above ground conditions for healthy plants with enhanced defenses Stress pests Enhance beneficials
Healthy plants with minimal pest damage
6. Reactive soil/nutrient management
2. Build healthy soil (below ground habitat conservation & enhancement)
4. In-season management to reduce crop stress and/or optimize yield and quality

Figure 1. Ecological field management framework.

Building soil strengths

- *Add large quantities of organic materials on a regular basis—animal manures, composts, tree leaves, cover crops, rotation crops that leave large amounts of residue, etc.* Soil organic matter and its management are at the heart of creating healthy soils[11,12] that have significant internal strengths that produce healthy plants that have good defense mechanisms. These characteristics include good nutrient availability, good water (and air) relations, good conditions for plant roots to grow and explore, production of plant growth stimulating compounds by microorganisms, disease suppression, low weed seed populations, etc. However, care must be taken to not overload soils with nutrients by continually using large quantities of organic materials such as composts from off the farm.
- *Use different types of organic materials because they have different effects on soil biological, chemical, and physical properties.*
- *Keep soil covered with living vegetation and/or crop residues by using cover crops, sod crops in rotations, and/or reduced tillage practices.* This encourages water to infiltrate into the soil instead of running off the field, taking sediments (and organic matter) along.
- *Reduce soil compaction to a minimum by keeping off fields when they are too wet, redistributing loads, using traffic lanes, etc.*
- *Use a variety of practices to reduce erosion.* These include some mentioned above, such as keeping soil covered with living vegetation or crop residue (using cover crops, rotation sod crops, and reducing tillage), as well as other practices such as terracing, grassed waterways, strip cropping along the contour by alternating a row crop with a sod crop, using natural or planted buffers between fields and streams, etc.
- *Use practices to supply supplemental fertility sources, when needed, that better match nutrient availability to crop uptake needs (which vary during the season).* This helps to reduce both weed and insect damage.

Creative use of a combination of the practices discussed above, such as a good rotation, adding organic materials to soil, and intensive use of cover crops—goes a long way to creating a more ecologically sound agriculture at the field level. It creates the conditions that are hospitable to plant roots, allowing the development of strong and healthy plants and helps promote the presence of naturally occurring biological control organisms. This promotes

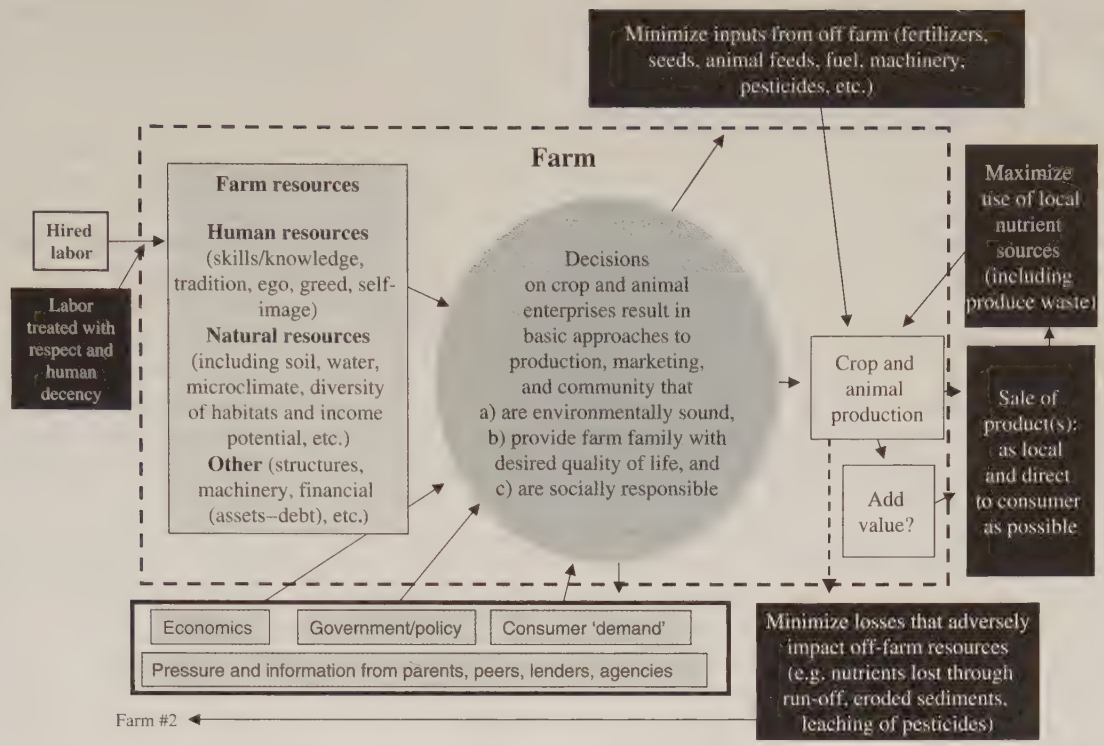
Minimize inputs from off farm (fertilizers, seeds, animal feeds, fuel, machinery, pesticides, etc.)
Farm
Farm resources
Human resources (skills/knowledge, tradition, ego, greed, self-image)
Natural resources (including soil, water, microclimate, diversity of habitats and income potential, etc.)
Other (structures, machinery, financial (assets–debt), etc.)
Hired labor
Labor treated with respect and human decency
Decisions on crop and animal enterprises result in basic approaches to production, marketing, and community that a) are environmentally sound, b) provide farm family with desired quality of life, and c) are socially responsible
Crop and animal production
Add value?
Maximize use of local nutrient sources (including produce waste)
Sale of product(s): as local and direct to consumer as possible
Economics
Government/policy
Consumer 'demand'
Pressure and information from parents, peers, lenders, agencies
Minimize losses that adversely impact off-farm resources (e.g. nutrients lost through run-off, eroded sediments, leaching of pesticides)
Farm #2
Some losses can become resources if properly managed
For example, manure or compost produced on one farm being used by a different farm

Figure 2. Ecological farm management framework.

characteristics of efficiency in use of nutrients and water, biological diversity above and below ground, self-sufficiency, self-regulation and resilience.

B. Routine ecologically sound practices during the season include such activities as scouting to see if pest problems are occurring and irrigating crops when rainfall is insufficient. Pruning tree crops to reduce humidity (and, therefore, fungal disease) is another one of these practices, as is cultivation for weed control.

C. Reactive management may be needed to save crops if, despite using a preventive approach, a pest outbreak or other issue occurs. In this situation, the release of beneficial biocontrol organisms may be the most benign approach although targeted (non-broad-spectrum), low persistence, low toxicity pesticides might be needed instead. The use of a foliar spray to quickly get nutrients into a plant during the season can help overcome some deficiencies that appear during the growing season. Reactive management becomes the last line of defense in ecological management, rather than the first or second.

Farm scale. We cannot just stop at the field scale, because practices that are carried out in a particular field are decided upon by farmers looking at their entire farm. What are the principles at the farm scale that will help guide a farmer making ecologically sound decisions that also provide the farm family with their desired quality of life, including adequate income, while being socially sound (see Fig. 2)?

- **Minimize inputs from off the farm** by building up soil organic matter and creating better above and below ground habitat (reducing tillage, using legumes to supply N to other crops, etc.).
- **Maximize the use of locally available nutrients** (manures, composts, cover crops, municipal leaves, etc.)
- **Mix animal and crop production whenever possible** to provide a number of benefits—such as more efficient cycling of nutrients on the farm (assuming that manure is handled well) and a reason to alternate sod (hay) crops with row crops. Mixed crop and animal production systems offer the potential for developing intensive biological synergies. These multi-species crop/animal systems can be extremely productive and provide opportunities for small and limited resource farmers to thrive—assuming they have access to credit and markets.
- **Add value to agricultural products** to provide family with added income.
- **Sell products as local and direct to consumer as possible.** This has two effects. Firstly it usually provides farmers with higher prices than they would receive through wholesale markets. Secondly, it creates more awareness of agriculture, agricultural issues, and provides a more direct connection between the public and their food. Because products are sold locally, this also creates the possibility of better cycling of nutrients.
- **Minimize adverse effects** on neighboring farms or the environment.
- **Treat hired labor with respect and human decency**, as the valuable resource that it is (this also reduces worker turnover).

Constraints to Ecological Agriculture in the US

The basic principles and many practices of ecological agriculture are well known. So why aren't they being practiced on most farms in the US and abroad? For more complex rotations to be used on a majority of conventional farms there need to be large and easily accessible markets for the additional products—for example, something other than corn and soybeans in the US corn belt. And while it makes ecological sense to reunite animals with the land that raises their feeds, decisions made by large corporations about where to place processing facilities and how they want 'their' animals raised makes it difficult for farmers to sell large numbers of animals outside that industrial system that has developed. (It should be noted that the buy-local movement has led to the development of new markets for some farmers through the food service industry. How large and long lasting an effect this will have is yet to be seen.)

Another constraint in the US is that certain commodities receive subsidy payments while others do not. Why leave a relatively dependable system for one with many economic unknowns?

A major constraint that we may have in the future has recently raised its head—the use of crops to produce energy. The price of corn increased by 60% in the fall of 2006, in response mainly to the increased use of the crop to produce ethanol. The USDA has projected that ethanol production will use 20% of the US corn crop in 2006[13]. With numerous ethanol plants currently under construction, ethanol will take an increasing share of the corn market and will compete with corn's use as an animal feed and feedstock for many byproducts such as high fructose syrup. With a more profitable corn crop, it will be difficult to shift corn belt farmers to more complex rotations. And with the accelerated push to produce ethanol (and other products) from crop residues, less organic matter will be returned to the land, leaving soils less fertile.

It is true that there are many farmers practicing ecological approaches to their farms. However, very few of these are large-scale growers trying to sell their products into the undifferentiated wholesale commodity markets. There are also currently some government subsidies for such farmers to follow more environmentally sound practices such as using cover crops or planting riparian buffer zones. However, even if an environmentally sound practice or two are used, rarely does a full-fledged ecologically based system develop. So farmers implementing a truly ecologically based system tend to be mainly small-scale growers who also try to capture for themselves some extra price above wholesale commodity prices—such as operators of Community Supported Agriculture farms (CSAs) and organic farmers that sell at farmers' markets, farm stands at the farm, and to local restaurants.

Over the past decade there has been a huge increase in interest among farmers in developing value-added products—from bottling milk, to making yoghurt, to farmstead cheeses, to processing meat and poultry, and so on. These farmers still represent only a small niche in US agriculture, although very important in some areas and definitely still growing. But the increasing desire for organic foods has been noticed by the 'big guys,' and we now have what should be a non sequitur—organic factory farms. Very large-scale organic dairies as well as vegetable and fruit farms are now common. And of all the outlets now getting interested in organic food, Wal-Mart is jumping in as part of its effort to attract upscale customers[14,15]. Thus, the small-scale farmer raising crops and animals ecologically needs to cultivate a local constituency—regardless of whether value is added to the products sold—and/or enter into values-based marketing networks with other farmers using their own brand(s).

Ecological Agriculture, Poor Countries, and Hunger

Possible alternate uses for crop residues is also a potential impediment in the Third World to implementation of an ecological agriculture that calls for returning as much biomass to the soil as possible. For example, dry cow dung in India is used as fuel and 60% of crop residues in China and 90% in Bangladesh are burned for fuel[16].

In Africa and other parts of the Third World there are also many other constraints to a more sustainable and ecologically based agriculture. Perhaps one of the largest has been the near wholesale elimination of government subsidies and other assistance to agriculture under recommendations and pressure from international organizations such as the International Monetary Fund (IMF). The abandonment of any real agricultural policy by many governments has left most farmers at the mercy of local market forces. Very low and declining yields are not uncommon as farmers attempt to eke out an existence on 'worn-out' soils[17]. Additional problems, such as endemic corruption and poor basic infrastructure such as inadequate roads and storage facilities, only make things worse. Without significant assistance, it is very difficult for farmers to escape a downward spiral of declining soil fertility and yields. The recent push on the part of private US foundations to implement a 'new green revolution' in Africa will most likely do little to alleviate hunger and poverty because it focuses on traditional green revolution technologies (high-yielding varieties, commercial fertilizers, pesticides and irrigation) instead of building an ecological agriculture, addressing structural inequalities, and having local groups and local and national governments take an active role in supporting agriculture[18]. It is certainly true that fertilizers will increase crop yields on many of the nutrient-depleted soils of Africa. Irrigation and other practices will probably also help. However, these technologies are neither unknown nor unused, and focusing on them misses the heart of the problem. The situation of Ghana's rice farmers has been described as follows: 'In 1983,

Ghana adopted free-market changes, followed by more in 1986. It earned accolades from the World Bank as the most promising West African economy after cutting duties and eliminating the aid that protected its rice sector. While the country's overall economy is expanding, poverty in the rural north has spiraled. Farming has been set back decades: Men harvest with small, hand-held sickles; women clean and sort rice by hand. According to the Ghana Rice Interprofessional Body, the country's three-ton-per-hectare ... yield is half what it could be.'[19] It is the neglect of the interests of small farmers by governments following 'free market' policies that has worsened the agricultural situation in many countries—including yield reductions in Ghana due to decreased fertilizer usage. In addition, relying on the routine use of costly imported materials such as fertilizers and pesticides, though helpful in emergency situations, is not a long-term solution to the problems of subsistence and small farmers. That will require the development of an ecologically based and diversified agriculture relying to the greatest extent possible on local resources and focused on building and maintaining healthy soils (as described above).

A group of developing nations (the Group of 20, with sometimes more and sometimes less than 20, led by Brazil and India) has made the subsidies of US and European farmers a key issue in the World Trade Organization's negotiations. Their unwillingness to accept the conditions imposed by the wealthy countries has led to the collapse of the Doha round of WTO negotiations that began in 2001 in Qatar. Certainly, the subsidies paid to farmers in wealthy countries allow products to be sold on the world market below the actual cost of production. This, of course, makes it difficult for farmers in the Third World to sell in the local market and to export abroad[19]. However, of all the problems of agriculture in the poor countries of the world, subsidies to farmers in wealthy countries is a relatively small issue compared to some of the others[20]. The main threat to farmers in the Third World is not that prices for agricultural products are too cheap because of subsidies to US and European farmers. This might be an issue for highly mechanized producers in the poor countries, but small-scale producers selling commodities on the world wholesale market just cannot compete directly with highly mechanized producers (with per person production perhaps 500 times or more that of a small-scale producer), wherever they are[21]. For example, Jamaican farmers cannot compete with US farmers in crops that do not receive direct subsidies, like carrots and onions, as well as in meat and chicken. Poor countries also compete among themselves, with the added coffee acreage in Brazil and Vietnam partially responsible for a few years of very depressed coffee prices worldwide. Vietnam, Taiwan and China are selling vegetables into the Philippines.

It is estimated that US corn entering Mexico under the NAFTA agreement has put some 1.5 million Mexican farmers out of business[22]. But this is primarily due to opening up markets by doing away with Mexico's protective tariffs—a 'remedy' or 'growth strategy' recommended to Third World countries by the IMF, the World Bank, and many NGOs—with the subsidies that US corn growers receive only making things somewhat worse. Even without the subsidies, highly mechanized farmers in the US will be able to produce commodity crops at prices below the price that will permit the subsistence of a small farmer growing those crops on a small plot in the Third World and trying to sell some portion in the local markets. Add to that, the takeover of the agricultural input industries—as well as purchasing, processing and selling of agricultural products—by large transnational corporations means that the small grower in the Third World is in a difficult situation, to say the least. One of the latest developments is the opening of large-scale European and US-owned supermarkets in poor countries. These supermarkets purchase produce only from large-scale growers, leaving the small farmer with the traditional markets, now less lucrative and serving fewer people. As a 2004 headline in the *New York Times* put it 'Supermarket Giants Crush Central American Farmers'[23].

Large-scale, highly mechanized agriculture is probably the greatest threat to the existence of billions of people, for reasons that will be discussed below. It is also taking the place of small-scale peasant agriculture in countries such as Brazil. It is occurring in response to the profits that can be made by selling certain agricultural commodities on the world market. Brazil, for example, with its relatively cheap land and labor, has very low costs of production for soybeans and exports approximately the same quantity of soy products as the US. In 2004, Brazil exported 20.3 metric tons (MT) of beans plus 14.8 MT of soy meal, compared with US exports of 29.9 MT of beans and 5.4 MT of soy meal[24]. Once large-scale agricultural production of commodities is profitable, more small peasants are forced from their lands by capitalist farmers—'legally' or illegally. That Brazil exports a lot of soybeans, sugar and oranges (or orange juice), and coffee certainly helps its balance of trade with the rest of the world. On the other hand, this can have very negative effects on the production of food crops for internal use by subsistence and small-scale commercial farmers.

Subsistence farmers forced off their land by a variety of forces are flooding into the cities of the Third World. With few jobs available they head to the slums and join the 'informal' economy as best they can. It is estimated by the UN that of the half of the 6 billion people in the world that lives in cities, about 1/3 of city dwellers live in slums—approximately 1 billion people. The conditions generally get worse as cities and slums become larger. The chairman of a district in Lagos, Nigeria described it as follows: 'We have a massive growth in population with a stagnant or shrinking economy. Picture this city ten, twenty years from now. This is not the urban poor—this is the new urban *destitute*.'[25] Most slum dwellers are removed from both the formal economy and from any chance of advancing and breaking the cycle of poverty and hunger. George

Parker ended an article on Lagos on a note of extreme pessimism: 'The really disturbing thing about Lagos' pickers and vendors is that their lives have essentially nothing to do with ours. They scavenge an existence beyond the margins of macroeconomics. They are, in the harsh terms of globalization, superfluous.'[24]

Samir Amin has estimated that 20 million highly mechanized and productive farmers can produce all of the world's food supply[26]. The number is probably significantly less, but let us assume his number. What will happen to those billions of people engaged in agriculture in countries that are not developing fast enough to productively absorb the farmers leaving the land? This is a recipe for a human catastrophe of the highest magnitude! In an era of more expensive energy and global climate change, the dependence of industrial agriculture on cheap energy and relatively stable climate might decrease its advantages over smaller scale more ecologically sound and resilient systems. However, for the foreseeable future, large-scale mechanized agricultural production remains a massive threat to the small farmers of the world.

There is a growing realization that countries need to take a more active involvement in their agriculture, promoting it, providing technical support to farmers, subsidizing inputs when needed, and using protective tariffs. (This is what the United States and other countries did for many years, and still do. The assistance to the farming sector in the US is huge, much larger than the subsidies going to directly farmers—from export subsidies to an extensive research and extension system to maintenance of the transportation infrastructure and so on.) Otherwise a lot of the countryside in the poor nations of the world will look as Jamaica does now—full of abandoned fields, with almost all food imported. Or, it will look like the Brazilian state of Mato Grosso, a powerhouse in highly mechanized production and exportation of soybeans—much on former rainforest land—and where one person controls 250,000 acres of soybeans. Or there will be some combination of the two. Regardless of how it plays out, all the alternatives seem to lead to a large portion of humanity being left in a very precarious state. The only hope of countering those outcomes is to reverse the negative effects of 'globalization' on most countries of the Third World. This means that governments must take an active part in promoting agriculture instead of relying on the neoliberal mythology of 'free markets' as the answer to all problems.

An ecologically based agriculture, focusing on small-scale farmers in the Third World primarily providing food for themselves and others in their countries, can be created. There are many techniques and approaches that have been demonstrated to be able to help such farmers produce good yields with few purchased inputs (for example, see reports on the conversion of much of Cuban agriculture to organic practices[27], the information on possibilities and practices of Biointensive Agriculture[28], and the evidence that ecologically based farming can provide high yields for small farmers[29]). Although much emphasis by agronomists in Africa is rightly placed on the emergency situation of supplying nutrients to vastly depleted soils, a more holistic approach to soil management will be needed to unlock the real potential of agriculture on the continent. However, significant changes will only happen through major governmental programs in each country—ones that mobilize the creativity and enthusiasm of the people and rely to the greatest extent possible on the country's own human and natural resources. From a humanitarian as well as ecological point of view, this is one of humanity's greatest challenges.

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Organic and conventional Washington State farmers' opinions on GM crops and marketing strategies

Leland L. Glenna[1,*] and Raymond A. Jussaume[2]

[1]Agricultural Economics and Rural Sociology, The Pennsylvania State University, University Park, PA 16801, USA.
[2]Community and Rural Sociology, Washington State University, Pullman, WA 99164, USA.
*Corresponding author: LLG13@psu.edu

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Abstract

A 1999 United States Department of Agriculture (USDA) policy on organic certification excluded the use of genetically modified (GM) crops. The decision remains controversial because it provokes debate over the fundamental meaning of organic agriculture. Some scholars, farmers and activists claim that organic agriculture represents a value orientation that is opposed to trends in industrial agriculture, of which GM crops are the latest product. Because organic farmers are a significant constituency in this debate, we examined their values and practices related to marketing, environment and GM crops. From a survey of 1181 Washington State farmers, we created a sub-sample of 598 crop farmers (fruits, vegetables and grains), of which 109 described themselves as organic (certified organic, moving towards organic certification and non-certified organic), and we analyzed organic and conventional farmer responses to a number of issues to discern comparative commitment to self-seeking economic interests. Results reveal differences among conventional and organic farmers on GM crops and several marketing and environmental values and practices, suggesting that there is some validity to portraying organic agriculture as an alternative vision to industrial agriculture.

Key words: organic agriculture, farmer attitudes, genetically modified crops

Introduction

Although certified organic production still represents a small share of overall agricultural production in the United Sates, it has expanded dramatically in the past decade. Certified organic land increased from 935,000 acres in 1992 to 2.3 million acres in 2000. And retail sales of organic produce have risen over the past decade to nearly $9 billion[1]. Because some of this expansion is the result of larger farmers and agribusinesses entering organic markets, social scientists like Guthman question whether the bifurcation of organic production represents an undermining of the 'transformative potential of organic agriculture' (p. 301)[2]. Michelson has made similar claims about organic agriculture in Europe[3].

Conflicting claims about the transformative potential of organic production highlight the need to examine the values that motivate organic and conventional farmers. One assumption that is common in the United States Department of Agriculture (USDA) publications is that farmers are turning organic primarily for economic reasons. Organic produce tends to bring premium prices; and even without premium prices, organic farmers often benefit from reducing input costs[1]. While Greene and Kremen acknowledge the ecological benefits of reducing chemical inputs, their litany of reasons for adopting organic practices emphasizes economic benefits: 'to lower inputs costs, conserve non-renewable resources, capture high-value markets, and boost farm income' (p. iii)[4]. Although economic issues probably influence all farmer decisions, some argue that organic agriculture is about more than increasing incomes because of the way it emerged in the 1940s as a challenge to the specialization, intensification and capitalization associated with industrial and 'modern' agricultural practices. Pfeffer contends that sustainable and organic agricultural movements emerged as a means of resisting industrial agricultural because the latter often led farmers to become dependent on purchasing agribusiness inputs[5]. Indeed, one of the early proponents of organic agriculture, Lord Northburn, claimed that small farmers

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needed to resist chemical inputs to persist in the face of economic consolidation[6]. More recently, Guthman has argued that 'organic agriculture has been positioned as the idealized alternative to industrial agriculture, both in social as well as ecological terms. And if the agent of agro-industrialization is profit-driven agribusiness, it is but a small step of logic to assume that organic farming is peopled by small-scale family farms' (p. 115)[7]. To those who see organic agriculture as an idealized alternative, it is ironic and contradictory when large agribusinesses venture into organic production[1,8].

If there is some validity to claims that organic farmers are adopting organic practices to establish an alternative system as much as to enhance their profitability, then it has relevance for policies that prohibit genetically modified (GM) crops in organic agriculture. GM crops are often associated with the conventional agribusiness-dominated system because most of the intellectual property related to GM crops is held by large agribusinesses, which enables them to gain greater profits from the farm production process[9–11]. As a result, 'biotechnology has come to symbolize the broad pattern of [dissatisfaction regarding] technological change within the food system for the broader public' (p. 7)[4].

When the USDA established national organic standards in 1999, it banned the use of GM crops in organic production. The USDA had originally planned to allow at least some GM crops, but after receiving over 275,000 letters, most of which were opposed to allowing GM crops, the USDA changed its position. Proponents of GM crops claim that the USDA erred in its decision because GM crops could have many ecological benefits. They claim that GM crops have the potential to be a powerful tool in organic production. For example, Bt cotton, Bt corn and Roundup-ready soybeans reduce chemical usage or enable the use of more benign chemicals (glyphosate), reduce fossil fuel use and enable soil-conservation technologies[12]. In contrast, farm and consumer groups offered three reasons for supporting the ban on GM crops: (1) Japanese and European markets expect organic produce to be GM free; (2) GM crops present ecological risks in addition to benefits; and (3) as Margaret Mellon of the Union of Concerned Scientists argued, GM-free organic agriculture would help small farmers to 'flourish'[13,14]. This third reason is important because it implies that farmers adopt organic practices to resist the concentration and consolidation of industrial agriculture.

It is difficult to distinguish between the economic and non-economic reasons why farmers may adopt organic practices because farmers adopt new production techniques and technologies for a variety of reasons. Furthermore, profitability and idealism are not necessarily mutually exclusive. Nevertheless, it is worthwhile to examine whether there are any significant differences between conventional and organic farmers because it may help to inject stakeholder perspectives into debates on the use of GM crops in organic agriculture. We seek to find whether such differences exist in data from a survey of Washington State farmers. If there is validity to the claims that organic farmers are interested in an alternative production system, we would expect to find attitudinal differences between organic and conventional farmers toward marketing and environmental practices in general, and GM crops in particular.

Framing the Analysis

A recent Council for Agricultural Science and Technology (CAST) paper claims that ethical conflicts often arise over how to evaluate the rightness or wrongness of an agricultural practice or regulatory policy, not because one side in the conflict is unethical and the other ethical, but because these perspectives represent different ethical traditions[15]. We believe that this observation is applicable to our efforts to understand different value orientations related to organic farming decisions and policies. By emphasizing the profitability of a farming practice, Greene and Kremen seem to assume farmers are *primarily* self-seeking economic actors[4]. In contrast, Guthman's assertion that organic farmers are resisting trends in conventional agriculture suggests that organic farmers are motivated *primarily* by principles and concerns for social consequences beyond their economic interests[7].

To develop a method for distinguishing value orientations of organic and conventional farmers, we relied on the CAST description of the three main ethical traditions that are often applied to agriculture. The first is the rights-based tradition, which holds that people have fundamental rights that should not be compromised, no matter what the consequences might be. This description would apply to libertarian or egalitarian perspectives. The second ethical tradition is utilitarianism, which argues that the rightness of an action is determined by the consequences yielding the greatest good to the greatest number of people. Therefore, consequences, not fundamental rights, are the main criterion for consideration. And the third tradition is virtue theory, which holds that people's actions should be motivated by principles governing social interaction, such as justice or fairness[15,16].

Although it is difficult to determine subtle differences between these three ethical traditions in farmer responses to a mass survey, we believe that at least two general ethical categories may be discernable: a libertarian perspective versus a communal (communitarian or consequentialist) perspective. The libertarian perspective would be evident in farmer responses reflecting an emphasis on their own individual rights and economic interests over the social or environmental consequences of their actions. In contrast, a communal perspective would be evident in responses that reflect concerns for social consequences, social principles, consumer interests, or environmental well-being. For example, a farmer advocating for policies that enhance his profitability and for less public-sector intervention would be a libertarian on marketing and environmental

issues. A farmer advocating for public-sector interventions to preserve something the farmer values or to accommodate consumer interests would be more consequentialist or communitarian than libertarian. We utilize this framework to compare conventional and organic farmers on their marketing and environmental practices and attitudes, with a particular emphasis on their willingness or unwillingness to try GM crops in their operations.

Data and Method of Analysis

The data analyzed in this paper were collected in a survey of agricultural producers throughout Washington State. Washington is second only to California in the United States in the number (548 as of 2001) of certified organic operations[1]. To draw our sample, we used a list of agricultural property owners that is maintained by the National Agricultural Statistics Service. A minimum of 10% of all agricultural property owners in each county in the state was selected to receive a survey. Four counties (King, Skagit, Chelan and Grant) were over-sampled, because the project team was particularly interested in analyzing differences across specific regions of the state.

Questionnaires were sent out to 3718 addresses on March 29, 2002. Dillman's tailored design method for mail surveys was followed[17]. A reminder postcard was sent on April 12th, and a follow-up mailing was sent to non-respondents on April 26th. To maximize return rates, particularly by reaching producers who may have been too busy with farm tasks in spring and summer, a third mailing was sent to non-respondents on November 13th. One-thousand twenty-six completed questionnaires were received, although due to refusals to answer specific questions, not all of these questionnaires were used in our analysis. The sample was adjusted by removing respondents who indicated that they sold less than $1000.00 of commodities in 2001, as well as removing cases where the potential respondent had moved, passed away, or received more than one survey. Some farmers received more than one survey because they owned more than one registered agricultural policy. After these adjustments were made, the final completion rate was 44.96%.

Of the 1181 farmers who completed the survey, we focused on 598 crop farmers, in part because beef and dairy have unique characteristics that may need to be studied independently. Of the crop farmers in our sample, 109 described themselves as producing at least some organic crops, and 489 farmed conventionally. Our analysis consisted of a straightforward cross-tabulation of responses by conventional and organic farmers on a number of marketing and environmental issues. We then conducted a similar analysis of organic farmers who were willing or unwilling to use GM crops.

Our reliance on farmers to self-report their status as organic (certified, moving towards certified, or uncertified) requires comment here. We included farmers who call themselves organic, even if they are not certified, for two reasons. The first is that anecdotal reports suggest that fruit and vegetable farmers, particularly those that are small in size and who market much of their produce directly to consumers, increasingly follow organic practices without getting certified because the certification process is costly and time-consuming. They may also consider certification to be unnecessary because the direct-sales relationship between farmers and consumers tends to be based more on personal trust, and thus does not require the standardization of trust that is associated with federal certification. The second reason is that we are interested in determining values of organic farmers generally, rather than the legality of particular organic farmer practices. Because self-defined organic farmers may differ from conventional farmers in the marketing strategies they utilize, it is quite possible that a broader definition of what constitutes organic production will enable us to more accurately assess whether there are value differences between organic and conventional farmers.

Results

An analysis of the data from our survey indicates that organic farmers are exceptionally innovative in terms of adopting alternative production and marketing strategies (Table 1). Organic farmers are significantly more likely than conventional farmers to sell directly to grocery stores, roadside stands, and farmers' markets, and are less likely to be part of a growers' cooperative. In addition, although only a small portion of our sample is involved in direct sales, organic farmers are more likely than conventional farmers to do so. We also found that organic farmers were far more likely to indicate an interest in participating in such activities in the future. This suggests that organic crop farmers in our sample have a greater interest in departing from the conventional agribusiness-dominated input and marketing system. Organic farmers are at the cutting edge in diffusion of innovation models, which creates an irony because the adoption/diffusion paradigm was 'developed at the height of the productivity paradigm,' while organic production is 'a challenge to this productivity paradigm' (p. 40)[18]. However, since marketing innovation activities may indicate self-seeking economic interest as much as seeking to establish an idealized alternative to conventional marketing practices, we also compared responses to variables in addition to those indicating marketing practices.

Responses indicate a difference in values between conventional and organic farmers (Table 2). Organic farmers are more likely to accept government regulations for environmental protection, more likely to be willing to sacrifice profits to conserve long-term productive capacity, and more likely to have concerns about the environmental effects of GM crops. This suggests that the organic farmers in our sample are more likely to evaluate environmental policies according to values that incorporate concerns beyond their individual economic interests. However, there are two exceptions. We found no significant difference on

Table 1. Percentage of conventional and organic crop farmers who plan to take these following marketing actions ($N = 598$, conventional = 489, organic = 109).

	Conventional (%)	Organic (%)
Farmer used this method in 2001		
Grocery stores	7	22**
Farmers' markets	7	32**
Growers' cooperatives	47	24**
Food cooperative	2	7*
Direct sales via catalogs or the Internet	3	10**
Community Supported Agriculture or subscription	1	7**
Roadside stands/farm stores	12	33**
U-pick sales	6	15**
Restaurants	2	14**
Farmer plans to		
Do more direct marketing to consumers	16	41**
Diversify the product mix grown on your farm	30	42*
Explore greenhouse production	5	25**
Integrate my operation by adding on-farm packing and processing	6	15**
Do more direct marketing to grocery stores and/or restaurants	7	22**
Utilize a brand or product labeling program (e.g., Green Labeling)	5	17**

Cross-tabulations of conventional and organic farmers significantly different on these variables at $P < 0.05$* and $P < 0.005$**. To save space, only significantly different results were included in the table.

Table 2. Percentage of conventional and organic crop farmers who agree or strongly agree with the statement ($N = 598$, conventional = 489, organic = 109).

	Conventional (%)	Organic (%)
Environmental regulations negatively impact farming practices in my county	79	61***
Local government should restrict non-agricultural development in important agricultural areas	60	68***
Land should be farmed so as to protect its long-term productive capacity, even if it means lower profits in the short-term	53	64*
If farmland is to be protected from urban sprawl, growers will need to accept restrictions on their ability to sell their land	40	48*
Consumer concerns about GM crops outweigh the overall benefits of using them	24	44***
If a GM crop were available in one of my commodity areas, I would be willing to try it	53	24***
The biggest threat to the economic viability of my operation is falling prices for farm products	86	66***
Free trade agreements will help my farm operation be profitable in the long term	33	15***
A 'buy local' campaign could increase the consumption of locally produced agricultural products	51	69***
The need is greater than ever for publicly funded agricultural research and extension programs	66	73***
Research and consultation by private agribusiness firms can replace most of the world done by university research and extension programs	15	11**
Consumers in my county should have more locally grown and processed foods available to them	48	71***
Direct marketing is an effective way to keep farms viable in my county	48	74***
There is a significant demand for organic agricultural products in the State of Washington	24	69***

Cross-tabulations of conventional and organic farmers significantly different on these variables at $P < 0.10$*, $P < 0.05$** and $P < 0.005$***. To save space, only significantly different results were included in the table.
Questions answered on a scale of 1–5. 1 = Strongly disagree, 2 = disagree, 3 = neutral, 4 = agree and 5 = strongly agree.

the variable related to compensation for wildlife habitat protection or the variable regarding compensation for restrictions on selling farmland.

Conventional and organic farmers also show differences on attitudinal variables related to economic and marketing issues (Table 2). Organic farmers are significantly more likely than conventional farmers to favor a more local emphasis on production and marketing, and significantly less likely to favor free trade or to trust agribusiness to replace the public sector for research. Organic farmers also are more likely to see a need for more publicly funded research. And, especially notable is the different attitudes towards GM crops. Organic farmers are much more likely than conventional farmers to express an unwillingness to

Table 3. Percentage of organic crop farmers who are willing to try GMOs who have used or plan to use one of these marketing methods compared to organic crop farmers unwilling to try GMOs who have used or plan to use one of these marketing methods ($N = 109$, willing = 25, unwilling = 56, neutral = 22).

	Willing (%)	Unwilling (%)
Farmer used this method in 2001		
Wholesale buyers, brokers, or packers	72	46*
Farmers' markets	33	39*
Growers' cooperatives	29	13*
Direct sales via catalogs or the Internet	21	5*
Roadside stands/farm stores	54	33***
Institutional	8	0*
Production or marketing contract	29	11*
Farmer plans to		
Do more direct marketing to grocery stores and/or restaurants	20	32**

Cross-tabulations of organic farmers willing to try GMOs and unwilling to try GMOs significantly different on these variables at $P < 0.10$*, $P < 0.05$** and $P < 0.005$***. To save space, only significantly different results were included in the table.

try GM crops and they are much more likely to say that consumer concerns about GM crops outweigh the overall benefits of using them. This finding could be interpreted in two ways. It could be seen as an indication that organic farmers are more concerned about the well-being of their consumers or it may reflect the recognition by these farmers of the importance of meeting consumer demands, even if the demands constrict farmer management choices. Regardless of the deeper significance of this interpretation, the result indicates that organic farmers are much more willing to recognize consumer concerns about GM crops and much less willing to accept policies that allow for the use of GM crops in organic production systems.

Although the differences between organic and conventional farmers may indicate a continuum rather than clear-cut categorical differences, we believe our findings validate the typology of libertarian versus communitarian. Conventional farmers' responses to the items from our questionnaire are more likely to fit in the libertarian market and libertarian environment types. In contrast, organic farmers are more likely to provide responses that place them in the communitarian or consequentialist category.

However, because not all organic (or conventional) farmers are alike, and because resistance to GM crops has been portrayed as a symbolic indicator of an idealized alternative to conventional agriculture, we deemed it important to examine in greater detail the differences between organic farmer responses to the variable that indicated a willingness to try GM crops. Among the 109 self-defined organic farmers in our survey, 23% replied that they were willing to try GM crops on their farms. It is important to clarify that we do not have any reason to think that these farmers are willing to violate the USDA ban on GM crops in organic production. Rather, we interpret it to mean that a small percentage of organic farmers might be in favor of reversing the USDA ban.

We did find some significant differences between organic farmers who were willing and unwilling to try GM crops on a number of practical and attitudinal issues (Table 3). The unwilling organic farmers are less likely than the willing organic farmers to take a libertarian position on the issue of payment for wildlife protection, but their positions are reversed on the issue of willingness to sacrifice short-term profits for long-term productive capacity. The only difference in the marketing activities variables we found between these organic farmers is that those unwilling to try GM crops are more likely to plan to do more direct marketing to grocery stores and restaurants.

On the attitudinal variables, the unwilling organic farmers were more likely to think that the environmental risks of GM crops are not well understood (Table 4). They were also significantly different from the willing organic farmers on a number of economic and marketing variables. The unwilling seem to be skeptical of the notion that agribusinesses could take over public-sector research. But the most obvious distinction is that the unwilling organic farmers place a greater emphasis on consumer interests and direct marketing.

Organic farmers who express an unwillingness to adopt GM crops are more likely than their willing counterparts to sell at farmers' markets and are more likely to plan to do more direct marketing to grocery stores and restaurants. However, it is difficult to make clear distinctions in this area because organic farmers in our sample who are willing to try GM crops are more likely than their unwilling counterparts to sell at roadside stands, to belong to grower cooperatives, to do direct sales via the Internet or catalogs, and to have production and marketing contracts.

It is also difficult to make clear distinctions on environmental and marketing attitudes between organic farmers who are willing or unwilling to try GM crops, because there were contradictory responses. The organic farmers who are willing to try GM crops were more likely to have a libertarian position on the question about getting paid to protect wildlife habitat, but less likely to have a libertarian position on the issue of forfeiting

Table 4. Percentage of organic crop farmers who are willing to try GMOs compared to organic crop farmers unwilling to try GMOs who agree or strongly agree with the statement ($N = 109$, willing = 25, unwilling = 56, neutral = 22).

	Willing (%)	Unwilling (%)
The environmental risks of GMOs are not well understood	72	86***
Farmers should be paid for their participation in wildlife programs including those to protect habitat	84	73*
Land should be farmed so as to protect its long-term productive capacity, even if it means lower profits in the short term	76	71*
Consumer concerns about GM crops outweigh the overall benefits of using them	20	59**
A 'buy local' campaign could increase the consumption of locally produced agricultural products	60	79**
Research and consultation by private agribusiness firms can replace most of the work done by university research and extension programs	16	5*
Consumers in my county should have more locally grown and processed foods available to them	67	78**
Direct marketing is an effective way to keep farms viable in my county	64	80**
There is a significant demand for organic agricultural products in the State of Washington	56	80**
Cooperative extension programs have been beneficial to my farm business	72	56*

Cross-tabulations of organic farmers willing to try GMOs and unwilling to try GMOs significantly different on these variables at $P < 0.10$*, $P < 0.05$** and $P < 0.005$***. To save space, only significantly different results were included in the table.
Questions answered on a scale of 1–5. 1 = Strongly disagree, 2 = disagree, 3 = neutral, 4 = agree and 5 = strongly agree.

short-term profits for long-term conservation of production capacity.

What we found most curious is that 72% of the organic farmers who said that they are willing to try GM crops also said that the environmental risks of using these crops are not well understood. Combining this with the fact that only 20% agreed with the statement that the concerns of consumers regarding GM crops outweigh the benefits of using GM crops suggests that organic farmers who are unwilling to try GM crops have a greater communal orientation than those willing to try them. That may be because organic farmers who are willing to try GM crops have less direct interaction with consumers. This is supported by the result showing that organic farmers unwilling to try GM crops are more likely to support local production and marketing projects. Furthermore, organic farmers who are willing to try GM crops are more likely to say that agribusinesses could replace publicly funded research. This suggests that the organic farmers unwilling to try GM crops may have a slightly higher tendency to favor an alternative marketing approach. However, we would need a larger sample and more specific survey questions to move beyond this speculation.

Conclusion

Social scientists have yet to develop a consensus as to why farmers shift from conventional to organic agriculture. Some tend to portray the decision as one based primarily on economic considerations. Others point to the historical origins of organic agriculture as a form of resistance to agricultural industrialization and contend that organic agriculture is an idealized alternative. It is difficult to find overwhelming evidence that organic farmers place communal concerns and social and environmental consequences above their own economic interests, at least in part because organic agriculture offers many economic benefits. In an attempt to overcome this obstacle, we used definitions of ethical traditions to distinguish between libertarian, consequentialist and communitarian value orientations to determine if organic farmers are more likely than conventional farmers to be concerned about more than individual economic interests.

Although our results do not always fit neatly into our analytical categories, we did find some significant differences between conventional and organic farmers' marketing activities and attitudes toward marketing and the environment. Organic farmers are less likely to be libertarian than conventional farmers. Most importantly, organic farmers are less willing than conventional farmers to use GM crops. For the few organic farmers who did express a willingness to try GM crops, there was a tendency to be more like conventional farmers than non-willing organic farmers on a number of variables. Based on our analysis of conventional and self-reported organic farmers in Washington State, therefore, we believe that there is at least some validity to claims that organic farmers have a different value orientation from conventional farmers, even though perceived economic benefits are also important in their decision-making process.

Our results cannot be generalized outside of the state of Washington, but they are consistent with more general claims that organic agriculture in the United States and other parts of the world represent something more to farmers than economic viability[7]. Recently, the Organic Trade Association, which represents agribusiness firms including Kraft and Horizon, pressed the US Senate and the USDA to revise organic standards to allow synthetic substances like xanthan gum to be allowed in products with an organic label[19]. The USDA may face similar requests to

overturn the ban on GM crops in organic production. Our findings indicate that when requests to revise organic standards are raised, the USDA might consider how most organic farmers may be opposed to such revisions.

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Feasibility of mulching technology as an alternative to slash-and-burn farming in eastern Amazon: A cost–benefit analysis

John Mburu*, Jan Börner, Bettina Hedden-Dunkhorst, Arisbe Mendoza-Escalante and Klaus Frohberg

Center for Development Research (ZEF), University of Bonn, Walter-Flex-Str. 3, D-53113 Bonn, Germany.
*Corresponding author: jmburu@uni-bonn.de

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Abstract

This paper addresses the question as to whether it is profitable to apply a mechanical mulching technology (MT) in the Bragantina region of Brazil and assesses the technology's feasibility as an alternative to the slash-and-burn practices of the Amazon. Using empirical data collected from a prototype assessment and a few secondary sources, the paper employs a cost–benefit analysis of 'with' and 'without' technology cropping systems (plots that applied the technology are compared with those that did not) to assess the financial and economic feasibility of investing in the MT. The analysis showed that the technology is profitable, both financially and socially, mainly because it is able to produce yields that are high enough to offset the costs, including the hiring of the mulching equipment. However, it may not be a feasible alternative to slash-and-burn farming unless certain conditions are fulfilled by farmers. Most of these conditions relate to farmers' adherence to a set of rules for the successful application of the technology. These rules include the abandonment of a single cropping cycle, typical for the traditional slash-and-burn system, and the adoption of two cycles of crop cultivation. In addition, farmers have to choose profitable crop combinations, such as cassava and beans for both cycles. Since most of the trial farmers did not meet these conditions, the technology received a notably low acceptability (8%). Further analysis indicated that the main reason for this trend was the increase of total labor requirement (by 32%), though the technology reduced labor demand during land preparation to almost zero. Similarly, there was a 22% increase in requirement for inorganic fertilizers. Thus, compared with the slash-and-burn practices of the Amazon, the MT can be regarded as a more intensive method of farming which gives higher crop yields but demands higher quantities of inputs such as labor and inorganic fertilizers. The paper concludes by deriving policy implications for the feasibility of the MT as an alternative to slash-and-burn agriculture in the Amazon. Among these is the importance of creating incentives to extend the cropping period from one to two consecutive cycles. Moreover, the necessity to conduct further studies after the technology has been adopted by the farmers is underscored.

Key words: alternatives to slash-and-burn, Amazon, Brazil, cost–benefit analysis, mulching technology, sustainable agriculture

Introduction

Although the traditional practice of slashing and burning fallows is a cheap method of land preparation in the Amazon, several disadvantages are associated with it. Denich et al.[1] document that burning of fallows leads, through volatilization, to losses of soil nutrients (nitrogen, sulfur, phosphorus, potassium, calcium and magnesium). In addition, there are losses of soil biomass and the local populations incur external costs due to smoke and accidental fires[2,3]. To overcome these problems, a mechanized, fire-free land preparation technology which is characterized by simultaneous bush clearing and mulching of fallows has been developed. Through this technology, carbon losses are considerably slowed down and soil nutrients are availed to cultivated crops for longer periods. The mulch left in the fields also helps in improving soil conditions and preventing erosion. Thus the farmers are able to increase their crop yields per unit area of land[4]. In this regard, the mulch technology can be viewed as a possible alternative to slash-and-burn practices as it would enhance farmers' level of production through increased land productivity and sustainability of fallow systems.

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The mulching technology (MT) can hypothetically be regarded as a type of technological change that results in changes of the total factor productivity. This implies that if prices of output and inputs are kept constant, farmers can produce a higher output with the same inputs, or the same output with fewer inputs. This may also mean that the efficiency or productivity of one or more inputs used in the production process is increased and total costs of production per unit of output are reduced. Kato[5] and Mendonca et al.[3] indicate that labor is a major constraint to the sustainability of the slash-and-burn practices and conclude that this factor could be an important constraint that farming households have to consider when deciding whether to adopt or reject any appropriate technology for land preparation. There is particularly a shortage of labor during land preparation, leading to delayed planting and hence reduced yields. The MT has been developed for the Bragantina region with the anticipation that it will assist to overcome this problem, and reduce the losses of nutrients and biodiversity from the fallow ecosystems.

Against this background, it can be hypothesized that the application of the MT enhances the efficient use of farm inputs, and enables farmers to raise their land productivity and to protect their environment. Several comparisons of crop yields realized from applications of slash-and-burn and mulching technologies have been done at an experimental level since 1997 and up to 2000[1,4–6]. The results of these comparisons are mixed, indicating that the MT can only achieve the level of yields of slash-and-burn farming if accompanied with the application of inorganic fertilizers. These external inputs compensate for the absence of ash-fertilizing effects experienced in slash-and-burn practices and the microbial immobilization of soil nutrients during the decomposition of the mulch layer. However, much of the research work on alternatives to slash-and-burn agriculture in the Amazon has so far focused on engineering aspects of land preparation equipment and machinery, agronomic characteristics and soil fertility issues[4,7]. There are no detailed economic studies that have been conducted to assess the profitability and feasibility of this new technology, from the perspective of both the farmers and the society. The latter is particularly important as the use of fire in slash-and-burn agriculture may generate losses or costs that not only adversely affect the landowners and farmers but also the society[3]. Thus, the objective of this paper is to conduct cost and benefit analysis in order to analyze the financial and economic profitability of the mulch technology and therefore justify its feasibility as an alternative to the slash-and-burn practices among the farmers of the Bragantina region, eastern Amazon. Using the concept of 'with' and 'without' project (here mulching technology), the paper conducts the cost–benefit analysis at two levels: private and social. At the private level, only the costs and benefits accruing to the farmers are considered, while at the social level, shadow pricing of cost and benefit streams has been applied and external costs arising from the slash-and-burn system have been incorporated.

The rest of the paper is outlined as follows: the next section discusses the study area and data generated through farmers' trials of the MT and how the analysis is conducted. The results of the cost–benefit analysis are discussed and conditions necessary for the feasibility of MT as an alternative to slash-and-burn practices are identified in the third section. Finally, some concluding remarks and policy implications are mentioned in the last section.

Study Area and Methodology

The Bragantina region

The data analyzed in this paper were collected in early 2004 from different field trials of the MT in the Bragantina region of eastern Amazon in Brazil. The region is located in the north-eastern part of the state of Pará. It occupies an area of 20,000 km^2 and has a population of 463,680 inhabitants. Most of the region is suitable for agriculture, with most areas covered with secondary forests of various ages and fields with annual cultures, plantation crops and pastures[7]. The cultivated areas are dominated by small-scale farmers who apply fallow-based farming systems which rely heavily on burned ashes for the supply of soil nutrients. During the current survey, the land holding size for small-scale farmers in the region was found to be 21.17 ha per household. Although commercial farms and cattle holdings have expanded into this region, the area can still be termed as culturally homogeneous compared with more recently colonized parts of the Amazon[8].

Slash-and-burn agriculture has been practiced for several decades in the Bragnatina region. It is characterized by a fallow-based farming system on a continuous piece of land, whereby after cropping for 1–2 years, the land is abandoned for the fallow period which lasts for an average of 6 years. Due to demographic pressure, the fallow period is increasingly becoming shorter, making the secondary vegetation (*capoiera*) lose its vitality and hence leading to forest degradation, deterioration of soil conditions and decreasing agricultural yields[1]. Following the introduction of the MT to overcome these and the other previously mentioned disadvantages of the slash-and-burn practices (see the Introduction section), farmers were expected to cultivate the cleared land for 4 years (two crop growing periods, each of 2 years) but maintain the 6-year fallow period. Moreover, they were expected to increase their capital investments as land cultivated through the MT requires additional external inputs such as fertilizers. Important annual crops grown in the region and used in the cost–benefit analysis include cassava (mainly for flour), beans, rice, black pepper and corn.

On-farm testing of the MT

The MT involves application of a high-powered tractor coupled with vegetation-chopping equipment (hereafter mulching equipment)[4]. This equipment cuts the bushes (trees, grasses, etc.), chops them into chips of less than

4 cm^3 and lays them as mulch on the top soils. During crop planting, inorganic fertilizers have also to be applied as the decomposing mulch ties up the soil nutrients, a factor that can contribute to substantially low yields[5].

On-farm trials of the MT have been conducted by farmers in the Igarapé-Açu and Bacarena municipalities of the Bragantina region since 1998. Yet, most farmers (96% of 61 smallholders) who volunteered to carry out the trials started at the end of 2001 or at the beginning of 2002. In both municipalities, farmers were supplied, free of charge, with all the necessary inputs (mulching equipment, seeds, fertilizers and pesticides) but they were expected to provide labor for all farm operations. In Igarapé-Açu, farmers decided on the size of the area cultivated as well as the crops to be planted, whereas in Bacarena, the experimental design was defined by the Albras, an aluminum mining company. The Albras had incorporated the MT into its social and environmental development project because of a legally imposed requirement to compensate local communities for the negative environmental effects of aluminum production. In both municipalities, extension on MT was provided by researchers from the Brazilian Agricultural Research Corporation (Embrapa) and its trainees, such that the expected extension bias was minimal.

The cost–benefit analysis results presented in this paper are based on data collected from all farmers (61) who by February 2004 had tested the MT in their farms and also practiced slash-and-burn in separate plots. These data cover all yields from the 2001/2002 cropping season, maize and bean yields from the 2003/2004 cropping season (second season) and partially harvested cassava that had been planted at the beginning of 2003. The full cassava yields for the second cropping season were extrapolated based on what had been harvested by February 2004. In addition, plot-specific data from seven farmers who had grown cassava and beans on slash-and-burn plots were used to increase the database on this activity. For the distribution, 74% of the 61 farmers came from Igarapé-Açu municipality and the rest from Bacarena. All the additional seven farmers came from Igarapé-Açu municipality. A structured questionnaire was used to elicit the data from both groups of farmers. All farm inputs (including labor) and costs incurred by farmers during these trials were recorded systematically using recalling questions. In addition, farmers were requested to recall and state the yields realized from each crop they cultivated during the different cropping cycles (see the subsection on 'Choice of crop enterprises and cropping cycles' scenarios').

'With' and 'without' technology ex post *comparisons*

The use of cost–benefit analysis in this paper allows the determination of the worth of investing in the MT. The methods of cost–benefit analysis are advanced, allowing project analysts to determine viable and non-viable investment initiatives. Of importance has been the 'with' and 'without' project *ex ante* comparisons which consider costs and benefits arising from a proposed investment ('with' project) and compare them with those arising from an existing situation or the 'without' project alternative. This concept is applied in this paper to assess the feasibility of the MT being used as an alternative to the traditional slash-and-burn practices of fallow farming.

The current analysis uses *ex post* data collected from an on-farm assessment of the MT by the farmers. The investment alternatives 'with' and 'without' MT (hereafter 'with' MT and 'without' MT respectively) are used to generate the incremental net benefit arising from the application of the MT in the cultivation of various crops/crop combinations. This incremental net benefit is then discounted at an appropriate discount rate and for the number of years covered by the cultivation and fallow cycle in order to generate the net present value (NPV) or the present worth of incremental net benefit of investing in MT[9]. This can simply be written as:

$$NPV_{(\text{with MT})} - NPV_{(\text{without MT, i.e. with slash-and-burn})} = NPV_{(\text{MT use})},$$

where $NPV_{(\text{with MT})}$ is the NPV of cultivating a certain crop/crop combination while applying the MT, and $NPV_{(\text{without MT, i.e. with slash-and-burn})}$ is the NPV of cultivating the same crop/crop combination (as with $NPV_{(\text{with MT})}$) using the slash-and-burn practices. $NPV_{(\text{MT use})}$ is the NPV indicating the incremental net benefit due to the application of the MT. The NPVs reported in this paper are for the $NPVs_{(\text{MT use})}$ only.

The criterion provided in economics literature for choosing a viable or profitable investment is that the NPV has to be positive. In the comparison of two investments (say an old one and a new one) in order to gauge which one is to be retained or adopted, as is the case in this paper, the NPV of the old or existing investment is subtracted from that of the new one. The new investment is qualified as a feasible alternative if the calculated NPV is positive. This implies that such an analysis can be used to justify whether the tested investment is a feasible alternative to the existing one, even in conditions where both investments are not profitable, i.e., both have negative NPVs[10]. In this paper, therefore, positive $NPVs_{(\text{MT use})}$ would only indicate that the MT is a feasible alternative to slash-and-burn farming. However, it is also indicated in the discussion of the results as to whether investing in the MT was profitable. To test whether the profitability and feasibility can be retained with slight variations of magnitudes of costs and benefits, a sensitivity analysis has been conducted.

Choice of crop enterprises and cropping cycles' scenarios

The cost–benefit analysis conducted in this paper does not include all the 39 crop enterprises grown during the MT trial period as farmers did not have similar crops/crop combinations. Confronted with this problem, a quantitative

Table 1. The number of plots analyzed for each investment alternative.

Scenarios	Number of plots per investment alternative		
	Cassava flour	Cassava flour and beans	Cassava flour and maize
Two-cycles scenario	1 (7)[1]	3 (7)	1 (19)
First-cycle scenario	12 (7)	7 (7)	7 (19)

[1] Numbers in parentheses represent the number of plots where the slash-and-burn practices were applied. NPVs calculated for these plots are subtracted from those estimated from the 'with' MT plots in order to justify the feasibility of the MT.

analysis of the most frequent crops/crop combinations cultivated by farmers, in both first and second cycles, was conducted. The crops/crop combinations identified through this analysis were cassava for making flour (hereafter referred to as cassava flour), cassava flour and beans, and cassava flour and maize (corn). In the second cropping cycle, these three are represented by about 80% of the cultivated crops/crop combinations.

The MT allows farmers to adopt two cropping cycles, each lasting for 2 years, as opposed to the single cycle of the slash-and-burn system. However, most farmers followed their traditional practice of cultivating plots for only one cropping cycle and only 8.2% of the 61 farmers went ahead to cultivate land for the second cycle. This was not in line with the advice provided by scientists who introduced the MT[5]. When asked for the reasons of not embarking on a second cropping cycle, many farmers reported negative experiences with second cycle crops under slash-and-burn. This may suggest that uncertainty with regard to the performance of the new technology was the main reason for risk-averse farmers not to extend the cropping period.

With a very small sample of farmers (8.2%) who tried the MT in accordance to the set guidelines, comparison of 'with' and 'without' MT alternatives is likely to produce inconclusive results. To overcome this problem, two scenarios, featuring the above crops/crop combinations and the variations of the cropping cycles, are developed. These are labelled 'two-cycles' and 'first-cycle' scenarios (Table 1) and are discussed in detail in the subsequent paragraphs of this section. Further, the analysis is done on a per hectare basis and not per farmer. Thus all costs and benefits are presented as averages per hectare. A certain crop/crop combination within a given scenario forms an alternative for investing the MT. With three crops/crop combinations and two scenarios, there are a total of six different investment alternatives (three per scenario). A total of 12 alternatives of one-hectare model farms were developed: six for the slash-and-burn and six for the MT.

For the 'two-cycles' scenario, costs and benefits data are analyzed from 8.2% of the 61 respondents who had the above selected crops/crop combinations in their first and second cropping cycles. In addition, other kinds of crops grown by the same farmers in the second cycle were included, though, as it was found out later, only rice featured in the case of cassava flour and maize combination. The 'two-cycles' scenario fits very well with the specifications of the scientists who introduced the MT. It also allows the analysis of farmers' preferred choices of crop combinations in one of the study areas, Igarapé-Açu municipality, where about 83.3% of the 61 farmers were given the option to choose their own techniques of crop husbandry. However, with the exception of the cassava flour and beans alternative the number of plots analyzed within this scenario is too low to warrant conclusive comparisons with slash-and-burn plots.

In the case of the 'first-cycle' scenario, only the first cropping cycle of the farmers with the above selected crops/crop combinations is considered for the MT investment. Hence, the cropping period has the same length (one cropping season) as in the slash-and-burn system. All farmers with a single cropping cycle are included in this scenario. Further, farmers that planted two cycles are included without considering their costs and benefits of the second cropping cycle. In this case, we analyze a situation that could have arisen if all the farmers had opted for a single cropping period.

The NPVs calculated from costs and benefits of each of the above six investment alternatives in these scenarios are compared with those analyzed from the slash-and-burn plots ('without' MT plots). As Table 1 indicates, the number of slash-and-burn plots (figures in parentheses) are appreciably high to allow comparisons with the MT plots within similar investment alternatives.

Considerations of different costs and benefits

Types of costs and benefits included in the financial analysis. The costs and benefits used for the financial analysis are valued at the market prices faced by the farmers. The main cost components or outflows considered are farm inputs such as fertilizer, seeds and pesticides, hiring of the mulching equipment, labor (both family and hired labor) and transaction costs. The latter include contracting costs for mulching equipment and farmers' opportunity costs of time spent acquiring extension services. Family labor is valued at its opportunity cost using the local wage rate. In this case, it is assumed that the household members are likely to find employment elsewhere in the local area during the time of farm operations. Table 2 shows which outflows existed or were entered for the 'with' and 'without' MT comparisons.

The transaction costs incurred by farmers in order to secure contract services of the mulching equipment and acquire any extension information related to their application are valued from the opportunity cost of labor (local wage rate). It is assumed that farmers spent an average of one and a half days to acquire these services.

Table 2. Possible inflows and outflows of the 'with' and 'without' MT comparisons and their hypothesized relative levels.

	'With' MT	'Without' MT
Inflows		
Crop yields from 1st the cycle	−	+
Crop yields from the 2nd cycle	+	0
Total crop yields	+	−
Firewood/charcoal benefits	0	+
Outflows		
Labor (both family and hired)	−	+
Fertilizer and pesticides	+	0
Costs of hiring mulching equipment	+	0
Transaction costs for using the mulching equipment	+	0
Health costs	−	+
Accidental fires	0	+
Carbon dioxide losses to the atmosphere	?	?
Biodiversity losses	?	?
Contamination of household water sources (proxy: increased distance to go for water in far areas)	?	?

(+) and (−) denotes hypothesized relative levels (whether higher or lower, respectively) of inflows and outflows of the 'with' MT alternatives, as compared with those of the 'without' MT alternatives. (0) stands for the non-existence of the inflow and outflow and (?) means it is difficult to determine the monetary value of the outflow from the collected data.
Source: data adapted from Denich et al.[4]; Mendoza-Escalante et al.[8]; Denich et al.[1]; Kato[6] and Kato[5].

The inflows or benefits arise mainly from the crop yields harvested from the cultivated plots. These are captured mainly through the calculation of the gross value of production (GVP), which is basically the crop yields multiplied by the farm gate prices. The GVPs for the 'without' MT scenario were calculated from a single cropping cycle while those of the 'with' MT scenario were derived from two cropping cycles (see also the subsection on 'Choice of crop enterprises and cropping cycles' scenarios'). For the 'without' MT scenario, the value of firewood collection is included in the analysis among the benefits. This benefit arises because farmers practicing slash-and-burn usually collect the post-burning residues (half-burnt wood) and use them as firewood for roasting of cassava flour, cooking, or charcoal production[11,12].

Drawing on past studies conducted in the Amazon on slash-and-burn land preparation and its alternatives, several hypotheses have been made on how different inflows (benefits) and outflows (costs) would vary if MT is introduced[1,4,6,8]. These changes are presented in Table 2 and denoted with (+) and (−) for increases and decreases, respectively. Outflows indicated with question marks (?) are difficult to predict, while those marked with a zero (0) do not feature in the literature as having any consequences on the technology employed in land preparation. Although the specific outflows and inflows are not the core subject of analysis and discussion in this paper, it is important to consider the influence they are likely to have on the incremental net benefits calculated from the 'with' and 'without' MT scenarios. This influence is captured in the discussion of different cost categories in the subsection 'The relevance of crop yields in influencing the feasibility of the MT' and through the sensitivity analysis conducted in subsection 'Sensitivity analysis'.

Types of costs and benefits streams included in the economic analysis. All the inflows and outflows considered in the financial analysis (see subsection above) were also used in the economic analysis after calculating their shadow prices. Shadow pricing was applied in the economic analysis in order to ensure that the financial inflows and outflows reflect their opportunity costs or real scarcity in society [for the society, only the regional level (Bragantina region) is considered]. Thus, for the economic analysis, the traded and non-traded farm outputs (mainly crop yields) and inputs are revalued to reflect their shadow prices. In addition, unpriced negative impacts such as costs of accidental fires and illnesses caused by smoke are included among the outflows of 'without' MT analysis. The data for these two economic outflows were elicited in 2002 by Mendoza-Escalante et al.[8] through interviews of 271 randomly sampled farmers in the Bragantina region. During this survey, farmers were asked to give monetary estimates of any losses they had incurred as a consequence of accidental fires (e.g. death of livestock, burning of fences, destruction of pastures, crops, orchards, plantations, etc.) and expenses incurred for the treatment of smoke-related sicknesses such as asthma, bronchitis and other respiratory ailments. In addition, farmers were asked to state the number of days they stayed without working due to the illnesses. Although farmers were requested to give the actual costs or losses incurred since 1991, only data for the three years prior to the survey (i.e. 1999–2001) are considered as it is presumed that the rest may not be reliable due to farmers' reduced capacity to recall all the information. This is reflected by the fact that about 60% of the values provided by the farmers fell on this period. The calculation showed that negative external costs arising from accidental fires and smoke-related illnesses are about R$ $22\,ha^{-1}$ and R$ $0.3\,ha^{-1}$ respectively. These values are far less than the costs estimated in the much more severely burnt western Amazon, where, for instance, Nepstad et al.[2] calculated R$ $254\,ha^{-1}$ as the losses from accidental fires. Notably, other important negative external costs arising from fires such as losses from closure of regional airports and traffic collisions due to impaired vision are not included in the current analysis, because interviews with local officials suggested little or no relevance.

In revaluing the tradable and non-tradable agricultural outputs and inputs, export and import tariffs, quotas and

other market restrictions that could artificially inflate or deflate prices were considered. To revalue labor, costs of land preparation had to be separated from the costs of other farm activities. This is because it had been assessed during the survey that there is a high and unfulfilled demand for labor during land preparation, which used to delay the operation. Thus the local wage rate paid during this period is a good estimate for the opportunity cost of labor and its marginal value product, and is therefore regarded as the economic rate. For the other farm activities (fertilizer application, weeding, etc.), it is estimated that the number of days that rural labor can expect to find employment during this period reduces by 12.5%. Thus, labor for these activities is revalued by multiplying the financial values with a conversion rate of 0.875. This is in agreement with Gaspary and Schmidt's[13] recommendation that, as a rule of thumb, the financial wages in developing countries should be reduced by 10–25% in order to arrive at the shadow wage rate.

Conducting the financial and economic cost–benefit analysis. Cash flows or dynamic cost–benefit analyses were modeled to measure the financial and economic returns of crop cultivation over a 10 year investment period (payback period). For the 'with' MT plots, cultivation is done for 4 years and then followed by a fallow period of 6 years. Thus the investment period ends when the fallow is ready for the next cultivation. Since the plots are ready for cultivation in the tenth year, a NPV of the anticipated 4 years of crop production is included as the residual value (salvage value) of the investment (i.e., investment cycle of 4+6 years, plus a residual value). On the other hand, the 'without' MT plots are at the end of the second cultivation cycle by the end of the tenth year. Therefore, it is assumed that this investment has no residual value since farmers are no longer interested in farming the plots after 2 years of cultivation (i.e., investment cycle of 2+6+2 years, without a residual value).

The cost–benefit analyses are conducted at constant prices (do not include interest and inflation). Both inflows and outflows are discounted over the 10 years' period to reflect the time value of money. A discount rate of 10% is used for both financial and economic analyses. On the basis of qualitative information gathered during the survey, this discount rate is assumed to reflect the opportunity cost of capital for the local farmers and the Bragantina region society. Since the opportunity costs of land are not included, the analyses conducted in this paper allow comparison of returns to land when using different technologies of cultivation.

Results and Discussion

Financial and economic profitability of the MT

Results of the financial and economic cost–benefit analysis are presented in Table 3. As described in the subsection "'With' and 'without' technology *ex post* comparisons" only the differences of the NPVs of 'with' and 'without' MT are stated in this table. For the cases where these NPVs are positive, it was also found that all the 'with' MT and 'without' MT investment alternatives were profitable (had positive NPVs). This indicates that the slash-and-burn agriculture is profitable to the farmers, but the application of MT would be more profitable. Since different scenarios of cultivation cycles and crops/crop combinations are tested, the results presented in this table also assess which investment alternatives would be profitable and feasible with the application of the MT.

Table 3. NPVs in R$ ha^{-1} of the incremental net benefit of using the MT.

	Crops/crop combinations		
Scenarios	**Cassava flour**	**Cassava flour and beans**	**Cassava flour and maize**
Financial cost–benefit analysis			
Two-cycles scenario	1165	484	−2587
First-cycle scenario	−1103	−1885	−1974
Social cost–benefit analysis			
Two-cycles scenario	1110[1]	546	−2560
First-cycle scenario	−1053	−1867	−1959

[1] Unlike in the other investment alternatives, the social NPV is lower than the private one for the cassava flour alternative of the 'two-cycles' scenario. This is because the labor costs of farm operations, other than land preparation, are considerably higher in the 'without' MT scenario compared with the 'with' MT to the extent that shadow pricing and additional external costs do not raise the social NPV of MT investment.

Both financial and economic values show a similar trend in all the six alternatives that have been tested. This indicates that the social pricing of costs and benefits does not play a major role in the analysis. This is mainly because most of the farming inputs and outputs are just traded within the region without being influenced by the prevailing import and export tariffs. Nevertheless, it is important to note that external costs, such as greenhouse gas emissions and biodiversity losses, have not been included in the analysis due to difficulties of generating the data during the survey period.

The calculated NPVs of the incremental net benefit of using the MT are positive only in the case of the 'two-cycles' scenario if either cassava flour or a combination of cassava flour and beans were planted for two cultivation cycles. While the positive results of both financial and economic analyses of the cassava flour alternative cannot be relied on, since only a single farmer tried the MT, the analyses of cassava flour and beans are important in that they indicate conditions under which MT can be a feasible alternative to slash-and-burn practices from both financial and social points of view. First, it is clear that this feasibility can only be achieved, both financially and socially, if two cycles of cultivation are adopted.

Secondly, using the technology and adopting the two cultivation cycles would not support this feasibility without farmers selecting profitable investment alternatives. Our results indicate such an alternative would be a combination of cassava flour and beans for both cropping cycles.

The results also indicate the rationality of farmers in investing in profitable endeavors, since the two alternatives with positive NPVs fall under the 'two-cycles' scenario which reflects the 'real' situation under which the MT had been anticipated to be a feasible alternative to slash-and-burn practices. However, one has to be cautious with this argument since about 21% of all the respondents were from the Bacarena trial area, where farmers were not allowed to make independent decisions on the kinds of crops to cultivate. As some of the scenarios are based on very few cases from the database, generalizability of the results is also limited. In addition, there exists a number of potentially confounding factors whose influence could not be ruled out. Among these are farming skills and soil quality, which are however expected to have minimal effects since we report the difference of NPVs of two systems on the same farm.

The relevance of crop yields in influencing the feasibility of the MT

The dominant feature of the profitable investment alternatives in MT is the capacity to produce yields that are high enough to offset the costs, including the cost of hiring the mulching equipment. Thus, the cassava flour, and cassava flour and beans alternatives with positive NPVs gave considerably higher crop yields than most of the investment alternatives with negative NPVs. Since the analysis conducted in this paper compares the incremental benefits of using the MT and those of the slash-and-burn approach, it is important to compare, at constant prices, the yields of the former with those of the latter. The cassava flour and beans alternative within the 'two-cycles' scenario is considered for this simple comparison of crop yields and costs due to its profitability and feasibility (Table 4). It was found that the total yields of this investment alternative of MT were higher than those realized from the single cycle of slash-and-burn by 53%. Thus, the considerable increase of yields when the MT is applied is a key factor for the profitability of the cassava flour and beans alternative of the 'two-cycles' scenario.

With these results, it can be deduced that the total yields of the MT investment in the cultivation of cassava flour and beans are considerably higher than those of the slash-and-burn farming mainly due to cultivation of land for a longer period (two cropping cycles instead of a single one). Moreover, this may be as a result of farmers' adherence to instructions on fertilizer application, since, as documented by Kata[5] and Kato[6], earlier farm trials had shown that fields prepared with fire-free technologies relied mostly on external sources of soil nutrients in order to produce higher yields than those realized from the slash-and-burn plots.

Table 4. Percentage increases of crop yields and costs of 'with' MT scenario as compared with those of the 'without' MT scenario of the financially feasible alternative of cassava flour and beans.

	Percentage increases of crop yields and costs (sum of 1st and 2nd cropping cycles)
Total crop yields (for both cycles)	53
Farm inputs	22
Labor	32
Hiring mulching equipment[1]	–
Total farm costs	122
NPV (from the cash flow)	16

[1] Notably, the hiring costs of the mulching equipment represent 41% of total costs of investing in MT. Comparisons are however not possible because this cost category is absent in the 'without' MT calculations.

When the total costs of the cassava flour and beans alternative of the MT are compared with those of the slash-and-burn agriculture, it was found that the former are enormously higher than the latter, by 122% (Table 4). Further investigation showed that most of the cost categories of this 'with' MT alternative had higher magnitudes of costs than those of the slash-and-burn. Specifically, the labor requirements of using the MT increased by 32%. This was because of increased labor requirements for additional or different farm operations, such as planting within mulched fields, fertilizer application and weeding. It was confirmed through both quantitative and qualitative data that although the labor demand for land preparation had decreased, the increase of total labor requirements when using the MT was one of the key reasons why its acceptability among the farmers was low (about 8.2%).

The costs of tradable farm inputs (mainly inorganic fertilizers) increased by 22%. These relatively high costs reduce the incremental net benefit of investing in MT. Thus, even if the benefits (crop yields) increase by 53%, the NPV increases by only 16% after modeling the cash flows for a 10-year period. Hence, slash-and-burn can be regarded as a less-intensive technology of farming which does not require high capital investment (labor and farm inputs), but gives lower returns in terms of yields. In contrast, mulching is a more intensive technology which demands higher quantities of fertilizers and eventually labor, but gives higher returns. This goes well together with the opinion of Mendonca et al.[3] that there is an inherent rationality to the use of fire in the Amazon mainly due to resource restrictions, such as labor and cash.

The results analyzed in Table 4 further support the argument that it is the relatively higher yields produced within the mulched plots that largely influence the viability

and feasibility of MT. Except for labor, the results are also in agreement with the hypotheses indicated in Table 2 concerning the behavior of different cost categories when MT is applied.

Sensitivity analysis

Sensitivity analysis is applied in the cost–benefit models to gauge which factors are likely to increase or reduce the expected returns on the use of MT and hence influence its viability and feasibility. Notably, the setting of the scenarios and the crops/crop combinations as explained in the subsection 'Choice of crop enterprises and cropping cycles' scenarios' can be viewed as an important variation that determines some of the conditions under which MT is likely to be a feasible alternative to slash-and-burn agriculture in Bragantina. Variations tested in the sensitivity analysis include the level of GVP, discount rate, cost of hiring the mulching equipment, labor costs (family and hired labor) and costs of tradable farm inputs. The results of varying the values of these benefit and cost streams by 25% (both reductions and increments) did not have any influence on the base NPVs of the MT investment. It was therefore deduced that the profitable and feasible MT alternatives are considerably insensitive (stable) to small increments or reductions of benefit and cost streams.

Conclusions and Policy Implications

Using the concept of 'with' and 'without' project this paper investigated the feasibility of applying a mechanical MT as an alternative to the traditional slash-and-burn practices in the Bragantina region. Its results reveal that this technology is profitable, both financially and economically. However, for it to be a feasible alternative to the slash-and-burn practices of the study area, certain conditions have to be fulfilled. The key condition is farmers' willingness to abandon the old tradition of a single cropping cycle, which is a common practice in slash-and-burn agriculture, and adopt two cycles, without which the MT cannot be profitable. Coupled with the two cultivation cycles, is the choice of profitable crops. The analysis has demonstrated that, for farmers to realize positive returns from the MT, certain crop enterprises or crop combinations have to be adopted. Among the combinations tested, growing of cassava flour and beans for the two cropping cycles emerged as a feasible investment alternative that could be suggested to the farmers.

The profitability of the MT is evidently due to the high yields produced by those farmers who fulfilled the above conditions. Thus the production of higher yields than in the slash-and-burn alternative has been identified as the dominant factor that can be associated with the technology. This implies that farmers adopting this technology in the future can raise their farm incomes and augment their food supplies.

The MT reduces the workload for land preparation for the smallholder farmers. However, the total labor requirements (for all the farm activities) increase when compared with the slash-and-burn alternative. Thus, at least for the moment, labor costs are likely to remain one of the crucial constraints that would hinder the financial and economic feasibility of the MT. Noting also that the case study farmers did not make own payments for the hiring costs of mulching equipment during the trials, this result has an important policy implication. To spur adoption of the technology, dissemination strategies could target farmers that are well endowed with both labor and capital. Unfortunately this would perpetuate an undesirable extension pattern, in that farmers who least need extension services will be targeted. In any case, advantages and disadvantages of the technology should be communicated to all the farmers. The extension message should inform them that although the MT is input intensive, it has a comparative advantage over the slash-and-burn farming because it is profitable when the stipulated guidelines are adhered to.

It was found that the conditions hindering feasibility of the technology are related to specifications developed by the scientists who introduced it. This would imply that intensive extension support services would be required if farmers are to abandon the slash-and-burn practices and adopt the mulching techniques. However, mechanisms to motivate farmers to follow the stipulated mulching guidelines, e.g. having two cycles of cultivation for four years, and crop husbandry practices such as application of fertilizers should be in place for them to realize the full benefits of using this new technology. An example of such a mechanism is a technology specific crop-yield insurance, which could buffer some of the uncertainties encountered when embarking on a second cropping cycle[14].

The capability of the MT to lower the negative effects of fire on the environment is a considerable advantage for both farmers and society. Admittedly, it is difficult to support fully the feasibility of the MT since, due to lack of data, not all the externalities of slash-and-burn farming were included in the analysis. Moreover, the costs of the farmers during the trials were highly subsidized and not all of them were allowed to make own crop husbandry decisions. Thus, it would be of imperative importance to conduct a similar analysis after farmers have adopted MT and shouldered all the farm costs as well as exercised their discretion in all farm decisions. It is only after conducting such an analysis that it would be possible to conclude without hesitation that MT is a feasible alternative to the slash-and-burn practices of the eastern Amazon.

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An assessment of grower perceptions and factors influencing adoption of IPM in commercial cranberry production

G. Blake[1], H.A. Sandler[2,*], W. Coli[3], D.M. Pober[4] and C. Coggins[5]

[1]Bard College, PO Box 5000, Annandale-on-Hudson, NY 12504, USA.
[2]University of Massachusetts Amherst Cranberry Station, PO Box 569, East Wareham, MA 02538, USA.
[3]Department of Plant, Soil and Insect Sciences, University of Massachusetts Amherst, Amherst, MA, USA.
[4]Department of Mathematics and Statistics, University of Massachusetts Amherst, Amherst, MA, USA.
[5]Simon's Rock College of Bard, 84 Alford Road, Great Barrington, MA 01230, USA.
*Corresponding author: hsandler@umext.umass.edu

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Abstract

A survey was developed and distributed to the Massachusetts cranberry grower community in 1999 to identify biological, educational, social and political barriers to the adoption of available integrated pest management (IPM) practices. The response rate for the 450 growers who received the survey was 54%. Approximately 80% of respondents claimed to practice IPM frequently and 16% identified themselves as occasional practitioners. Most growers practiced IPM because they agreed with IPM philosophy (80%) and believed it had environmental benefits (73%). Ninety-two percent agreed that more IPM-related research and education programs would encourage them to adopt practices they are not currently using. A significant percentage of respondents used multiple IPM component practices, with practices involving monitoring and detection of pests along with judicious use of pesticides being most common. Factor analysis was used to condense 104 potential responses to 22 factors, which were then used as predictors with six demographic variables (IPM adoption, education level, age, experience, farm size and work status). Demographic factors influenced a grower's tendency to incorporate IPM into routine farm activities. Full-time, highly experienced growers in charge of large operations tended frequently to use more IPM practices than less experienced growers who worked part-time and managed smaller farms. A large proportion of respondents agreed that IPM can reduce pesticide residues in food (92%) and the environment (96%), and can help to preserve beneficial insects (96%). Although many growers held the perception that IPM can pose measurable economic risk (and subsequently act as a barrier to adoption), growers appeared to feel less strongly about the economic benefits than potential environmental ones.

Key words: integrated pest management, *Vaccinium macrocarpon*, adoption, surveys

Introduction

General background

Adoption of integrated pest management (IPM) strategies for the farming community has been defined as a goal on national, regional, state and local levels. The endorsement of this goal has been in response to studies indicating that pesticide use could be reduced following implementation of IPM and that conventional chemical control strategies were responsible for widespread pest resistance[1]. IPM is a flexible management philosophy that emphasizes the need for suppression rather than eradication of pest populations[2,3]. Specific components of a cranberry IPM program include scouting for pests, application of pesticides in accordance with pre-established economic thresholds, and use of biological controls and cultural practices that alter or manipulate the environment to be less favorable to pests[1,4].

Many growers report using IPM techniques as their primary program for controlling pest populations[5–7]. Quantifying IPM success is challenging as many farmers choose to engage selectively in particular aspects of an IPM

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program[8–11]. Measurements of IPM adoption have ranged from reliance on self-reporting by farmers, assessments based on individual IPM practices employed or the use of key practices, to evaluation of farmer knowledge and decision-making criteria with regards to pest management strategies[12,13].

Development of successful Extension and research IPM programs for any commodity relies on feedback from grower groups to document current practices and future needs. Even with their limitations[7,14–16], surveys are legitimate methods for obtaining information about perceptions and adoption of IPM in agriculture. Previous researchers have identified factors affecting agricultural adoption of IPM to include variables operating on the individual or farm level such as age, farming experience, farmer education level, size of farm, farm income, as well as the cost and perceived benefits of IPM[17–19]. For example, a study of apple growers noted a negative association between use of specific IPM practices and age of farmers[12]. Another study focusing on IPM use by fruit and vegetable farmers in New Jersey concluded that education had a positive impact on IPM adoption[20]. Furthermore, a national survey found that IPM users tended to have less farming experience than did non-users[21].

Previous surveys have documented relationships between perceptions, behavior and IPM use. When considering the role of economic and environmental factors, IPM users were much more likely to have positive beliefs about the impacts of IPM on profit and yield than non-IPM users[8]. Barrientos and Anciso[17] found that the perceived economic risks associated with IPM adoption served as barriers to greater implementation by cucurbit growers in Texas. In a study of factors affecting IPM adoption by Wearing[22], the farmer's desire to conserve the natural enemies of pests was identified as an important environmental concern. In a survey distributed to all cranberry regions in North America, researchers found that growers were willing to adopt new and selective management practices provided they were both efficacious and environmentally friendly[23].

In this study, a mail survey was distributed to Massachusetts (MA) cranberry growers during the summer of 1999 to identify significant factors influencing cranberry IPM adoption. The overall objective of the survey was to compare farmer perceptions regarding the economic and environmental consequences of IPM among those growers who identified themselves as frequent, occasional or non-IPM practitioners, as well as to compare the suite of practices used by those growers. Questions in the survey were designed to identify relationships between grower perceptions and behavior with regard to the use and adoption of IPM practices. In addition, obtaining grower opinions on the value of existing IPM educational materials and programs and the effectiveness of current IPM practices for cranberries was also an important objective. Finally, we also sought to examine the influence of demographic factors, such as age and education level, on grower beliefs and adoption of IPM.

IPM and cranberry agriculture in MA

The topic of IPM is especially salient to MA cranberry growers as cranberry farms along the east coast have been identified as having more significant pest problems than other cranberry growing regions in the US. The climate, geology and soils of southeastern MA have proven ideal for growing cranberries and support a wide range of organisms (both beneficial and not) that also live in the agroecosystem. The long growing season and high summer temperatures of the region are especially conducive to the outbreak of cranberry diseases such as fruit rot[24]. In addition, the development of pesticide resistance among key cranberry insect pests, such as *Sparganothis* fruitworm and cranberry weevil, has been an increasingly significant problem for MA growers[25,26].

Cranberry agriculture in MA is different from that in other cranberry growing regions due to the large number of family farmers and growers with small acreage in the state[27]. On average, MA growers manage older, less productive bogs than growers in other states. Nevertheless, MA historically produced more cranberries than any other region until surpassed by Wisconsin (WI) in the mid 1990s[28]. This was a result of substantial acreage expansion that occurred in WI during the 1980–1990s. Notably, much of the acreage was planted to high yielding varieties in large farm parcels[29]. In contrast, MA growers have been limited in their ability to expand acreage significantly due to the lack of available land, high land prices, and environmental regulatory restrictions[30].

Despite changes in the proportion of fruit output from the various regions, the industry enjoyed a prosperous period up to the late 1990s. The high value of the crop permitted growers to include expensive pest management practices (such as the use of entomophagous nematodes) in their IPM programs. In the year following the distribution of this survey, the US cranberry industry experienced a sharp economic downturn as supplies greatly exceeded demand. Factors including increased importation of foreign cranberry products, increased production from the newly planted acres, and flat consumer sales contributed to the surplus[28].

Presently, small cranberry operations in MA are struggling to be economically viable. Many growers are considering selling or leasing their land or leaving cranberry production to pursue other full-time jobs[27]. Others have chosen to cut back on management practices, including scouting and the use of expensive chemicals or practices to save money until prices recover. Readers should note that this paper reflects grower views about IPM just prior to the economic downturn. Further examination of the effects of market collapse on grower use of IPM practices would be a suitable follow-up study to this paper.

Materials and Methods

Survey development and distribution

The survey was developed and distributed during the summer of 1999. General methodology for writing the questionnaire, preparation of the cover letter, follow-up letters, and multiple mailings was patterned as per Dillman[14]. The mailing list was obtained from the University of Massachusetts Amherst Cranberry Station and supplemented by the 1999 Massachusetts Department of Agricultural Resources 1999 Wholesale Growers Directory to generate a more inclusive list of cranberry growers in the state.

The survey was sent to 452 growers, approximately 90% of the estimated grower population in MA (J. LaFleur, Cape Cod Cranberry Growers' Association, and A. Davis, National Agricultural Statistics Service, personal communication, 1999). Because the population was so small and the mailing list was not absolutely inclusive, random sampling was not employed. Instead, the survey was sent to all growers on the mailing list. A minimum sample size of 217 (a response rate of 48%) would be necessary to achieve $\pm 5\%$ sampling error[15] and produce a credible sample.

The final survey consisted of an eight-page monarch-size booklet with 27 questions inquiring about: (1) grower IPM use; (2) major factors affecting grower adoption; (3) satisfaction with educational materials and programs produced by the University of Massachusetts Amherst Cranberry Station; (4) opinions about the economic and environmental consequences of IPM; (5) perceptions about the effectiveness of IPM methods in controlling major cranberry pests; and (6) demographic issues. Many of the questions had multiple parts, yielding a total of 104 potential responses per survey.

Questions were constructed to allow responses in one of three formats: choose one response from a list of choices (demographic variables); choose one response from three levels of possible activity (never, sometimes, or frequently) or importance (not, somewhat, or very); and choose one response from six levels of agreement (strongly disagree, disagree, mildly disagree, mildly agree, agree, or strongly agree). Unless specifically mentioned, reported results in which it is stated that growers 'agree' or 'disagree' implies the combination of results from the three levels of agree or disagree responses, respectively.

Statistical analyses

All analyses were carried out using SAS version 9.1 for Windows[31]. Descriptive statistics, including counts and frequencies of various responses, and counts and frequencies of various responses as a function of the demographic variables, were computed using PROC FREQ. Six demographic variables were identified: IPM adoption, educational level, age, years of experience, farm size, and work status (full or part-time). Excluding these demographic variables, factor analysis was conducted to identify underlying patterns among a group of related variables.

Factor analysis[32] was performed using PROC FACTOR. The 'varimax' orthogonal rotation method was used to ensure that the factors produced by this analysis would be uncorrelated with one another. Squared multiple correlations were used for prior communality estimates. Some of the assumptions of factor analysis may have been violated by our use of categorical, rather than continuous, data in the present study. Use of factor analysis on categorical variables is common in the behavioral sciences, and appears to provide valid results with these types of data[33]. This violation should not have any consequences on the validity of our conclusions about the existence and location of relationships and common variance among the variables analyzed.

Significant factors for each question were determined by keeping those factors whose loadings were greater than 0.30 in absolute values. Once these factors were determined, factor scores were created for each survey respondent. These factor scores were then used to develop multinomial regression models using PROC GENMOD. This allowed the investigators to determine the location of significant relationships between the continuous factor scores and the categorical (and often ordinal) responses to the questions regarding descriptive characteristics. Specifically, we determined which factors were significantly related to the six demographic variables listed above.

Results

Descriptive statistics

Of the 450 surveys that were mailed, 285 were returned, of which 243 were usable. The overall response rate was 54%, well above the expected return rate for most mail surveys of about 30%[14,15]. Presentation of the data categorizing the responses for the suite of management practices used for insects, weeds, diseases and general horticulture management are presented in Figures 1–4. Responses to questions describing growers' sentiments about IPM and its effectiveness in controlling major pests are presented in Figures 5 and 6. Responses to other questions are presented in the following discussion in text form only.

Demographic characteristics indicated that the majority of respondents were full-time growers (63%), older (33% aged 50–59 years and 27% aged 60 or over), educated (48% with college and 11% with graduate education) and experienced growers (34% with 11–20 years and 12% with 20 or more years of bog management experience). Forty-seven percent reported farming 10 acres or less, one-third farmed between 11 and 40 acres and 21% reported farming more than 41 acres.

According to the survey results, a significant percentage of respondents had a favorable perception of IPM, and were using numerous IPM practices in 1999. Approximately 80% of respondents claimed to practice IPM frequently

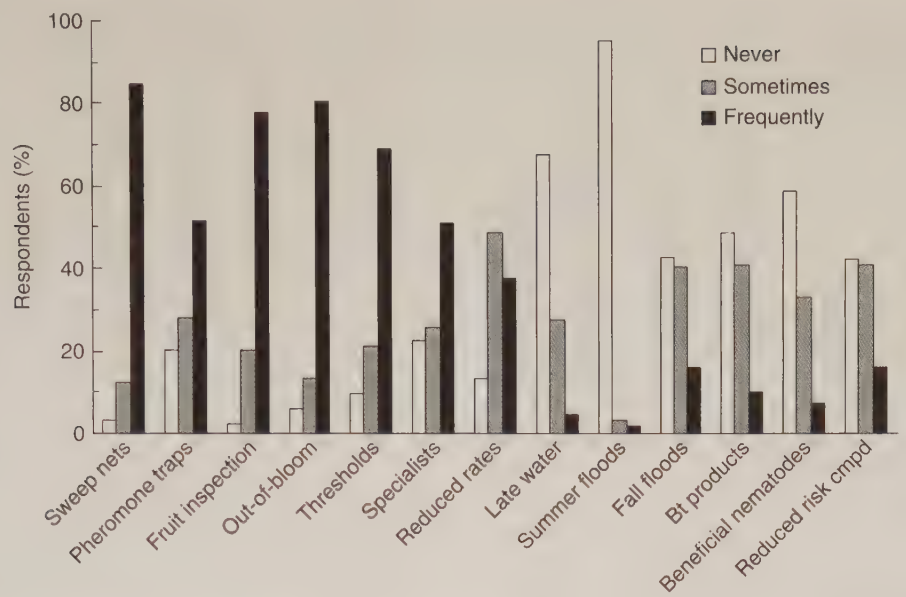

Figure 1. Percentage of respondents in 1999 MA grower survey who used various practices to monitor or manage cranberry insects. The various practices are: scouting using sweep nets; pheromone traps for determining peak flight; fruit inspection for cranberry fruitworm; determination of percent out-of-bloom for cranberry fruitworm; applying pesticides only after action thresholds were reached; applying pesticides based on advice of IPM specialists; using reduced rate applications; use of late water floods; use of short-term floods; use of Bt products; use of beneficial nematodes; and use of reduced-risk compounds.

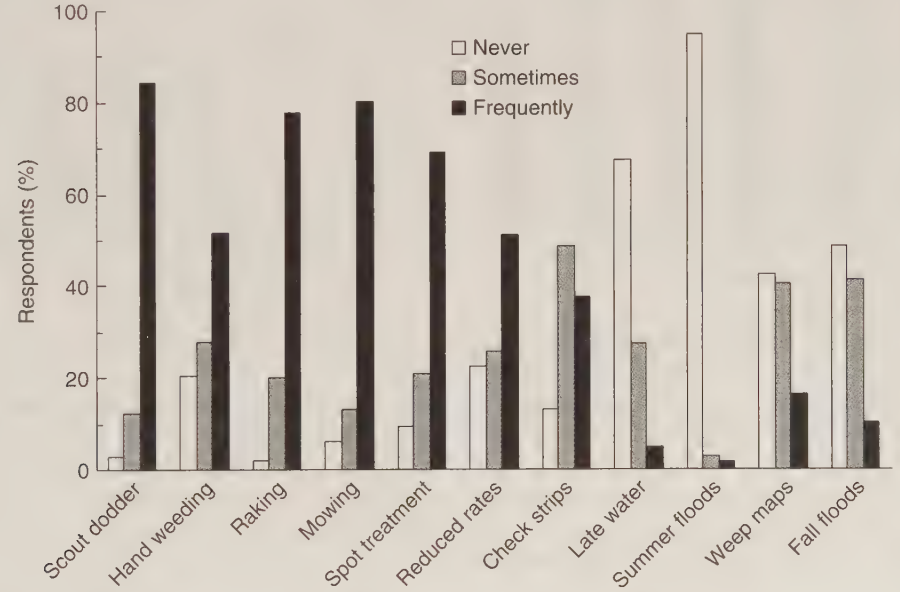

Figure 2. Percentage of respondents in 1999 MA grower survey who used various practices to monitor or manage cranberry weeds. The various practices are: scouting for dodder emergence; hand weeding; raking for dodder control; mowing broadleaf weeds; spot treatment with herbicides; reduced rate pesticide applications; using untreated check strips with a herbicide application; late water floods; short-term summer floods; weed mapping; and fall floods.

(FreqP), about 16% claimed to practice IPM occasionally (OccP), less than 3% said they did not use IPM (NonP), and less than 1% of respondents answered that they were not sure or did not know.

Growers adopted IPM practices for a number of reasons, among them environmental and economic benefits, and the belief that IPM is effective. The most popular reasons cited for choosing to practice IPM included agreeing with the IPM philosophy (80%), environmental benefits (73%), satisfaction with its effectiveness (59%), the belief that IPM saves money (57%), and personal and public health benefits (54%). Although growers certainly have

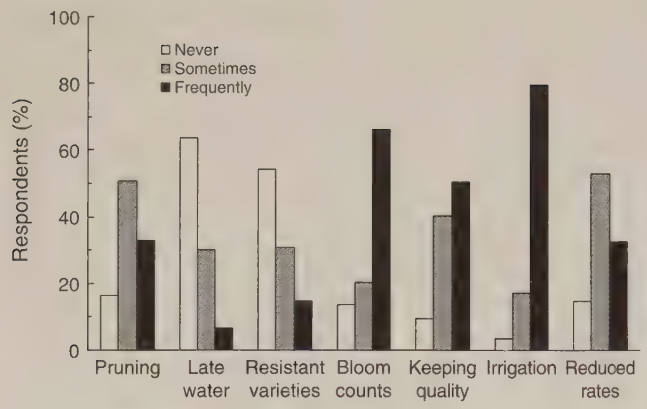

Figure 3. Percentage of respondents in 1999 MA grower survey who used various practices to monitor or manage cranberry diseases. The various practices are: pruning; late water floods; disease-resistant crop varieties at planting; using percent bloom counts to time fruit rot management; using keeping quality forecast; irrigation scheduling to minimize leaf wetness; and reduced-rate fungicide applications.

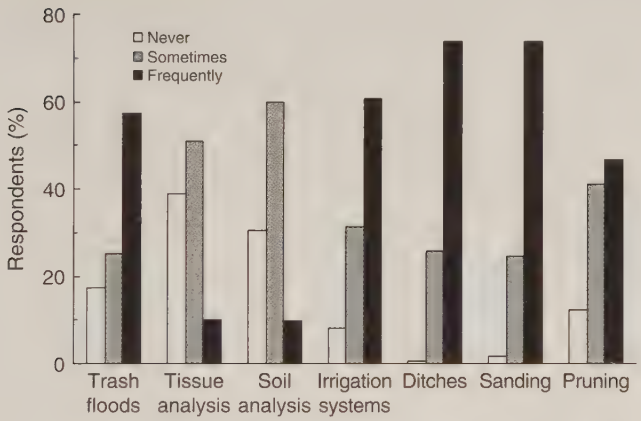

Figure 4. Percentage of respondents in 1999 MA grower survey who used various horticultural practices. The various practices are: post-harvest trash removal floods; leaf tissue analysis for nutrition management; soil analysis for nutrient and pH values; maximizing performance of irrigation systems; cleaning ditches; regular applications of sand; and regular pruning.

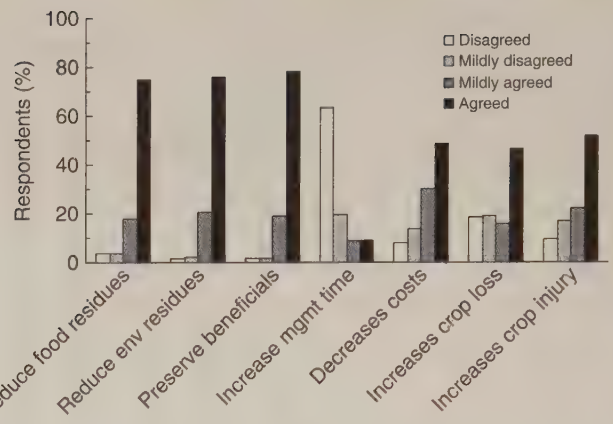

Figure 5. Percentage of respondents in 1999 MA grower survey who agreed or disagreed about the following statements: IPM reduces pesticide residues in food; IPM reduces pesticide residues in the environment; IPM helps preserve insects beneficial to the grower; use of IPM increases management time; use of IPM decreases the monetary costs of pest management; use of IPM increases the risk of crop loss; and use of IPM increases the risk of crop injury.

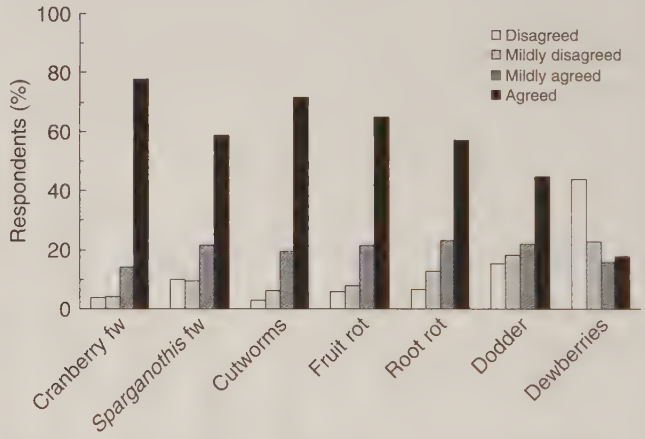

Figure 6. Percentage of respondents in 1999 MA grower survey who agreed or disagreed about the effectiveness of current IPM practices for: cranberry fruitworm, *Sparganothis* fruitworm; cutworms; fruit rot; *Phytophthora* root rot; dodder; and dewberries.

experienced pressure from neighbors and the public to reduce pesticide use[34,35], this did not appear to be an important factor motivating them to use IPM, as only 6% cited public pressure as a reason for practicing IPM. These results suggested that IPM is not just being employed by a few environmentally concerned growers, but rather has been adopted as a mainstream approach to pest control and that multiple benefits are perceived as attributable to IPM.

When given the opportunity to state why they did not practice IPM, 46% of the small subset of growers (5% of respondents) indicated they were satisfied with the effectiveness of non-IPM methods and thought IPM was too expensive. One-third of NonP growers thought IPM was too time-consuming and too risky. Two or fewer growers indicated that they did not understand IPM, thought IPM was too difficult to practice, or thought IPM did not work.

A significant percentage of respondents from the entire survey pool (72%) agreed or strongly agreed that the provision of a government cost-share program, which could help to offset the costs of IPM adoption, would encourage them to adopt more IPM practices. The survey also revealed that a similar number of growers were aware of the potential implications of the Food Quality Protection Act (FQPA) on future pesticide use (restriction or loss),

as this was cited as an important factor that might encourage many to adopt IPM practices they are not currently using.

Almost all respondents (92%) agreed that more IPM-related research and education programs and increased funding for IPM method development would encourage the adoption of underutilized IPM practices. Similarly, 88% of respondents agreed that the development of more on-farm demonstrations would encourage them to adopt IPM practices. On the other hand, the provision of crop insurance that would protect against loss due to IPM was not an issue that a majority of respondents demanded. Forty percent agreed or strongly agreed that the availability of crop insurance programs would encourage them to adopt IPM practices they were not currently using.

Over half (57%) agreed or strongly agreed that the creation of markets for IPM-grown cranberries would be an incentive for IPM adoption. However, less than 28% agreed or strongly agreed that public pressure would promote them to increase their use of IPM practices. This further confirmed grower claims that public pressure did not play a large role in their decision to adopt IPM in the first place. Perceptions about the risk of crop loss (77%) and vine injury (66%) as well as commodity price (53%) were the most important factors affecting pest management decision-making. In contrast, the cost of IPM consulting (42%), biological controls (28%), and reduced-risk pesticides (24%) were considered not to be important factors influencing pest management decisions.

The survey results also indicated that an overwhelming number of respondents (over 90%) seemed to be satisfied with Extension educational programs and materials provided by the University of Massachusetts Amherst Cranberry Station. Specifically, they agreed that these sources were helpful in providing information on how to use IPM techniques and in communicating the benefits of IPM. More than 95% of survey respondents claimed to rely significantly on Extension publications, personnel, and workshops as resources for information on IPM. The local grower association (88%) was also seen as an important resource, as were private consultants (69%). Respondents claimed to depend least upon trade magazines (49%) and pesticide company representatives (42%) for information on IPM.

When asked about factors influencing their decisions about when and if to carry out sprays for pest control, an overwhelming number of respondents (93%) claimed to be using economic thresholds as a primary basis for that decision, while only a very small percentage (2%) claimed to rely heavily on salesperson recommendations or the consideration of when other growers spray. Past experience with a pest (51%) and the first sign of a pest (57%) were cited as very important factors affecting the decision to spray, which suggested that many growers often do not use scouting and threshold recommendations at all times. Notable was the fact that 65% of respondents claimed to rely on a regular schedule as a somewhat or very important factor for determining the need for and timing of pesticide applications. Growers considered the advice of Extension personnel (55%) and private pest management consultants (45%) very important for determining the need to spray for pest management.

Practices involving monitoring of pests before they reach outbreak levels appear to have been carried out by a significant percentage of respondents for insect, weed, and disease management (Figs. 1–3). These include frequent use of scouting for insects with sweep nets (85%), scouting for dodder emergence (70%) and conducting bloom counts for fruit rot management (66%). Many also reported frequent use of strategies involving the judicious use of pesticides, such as application only after pests have reached economic thresholds (69%) and use of spot treatments for weed control (68%). Reduced rate pesticide applications were used frequently by approximately 35% of respondents for insect, disease and weed management. Methods generally perceived as more risky due to the increased likelihood of crop loss, vine injury or ineffectiveness[36–39], such as late water and summer floods, and the use of *Bacillus thuringiensis* (Bt) products, respectively, were used frequently by very few growers ($\leq$10%).

One-half to three-quarters of respondents claimed to be using a number of different crop management practices aimed at preventing development of pest and disease outbreaks, such as sanding, cleaning ditches, and post-harvest floods to remove leaf debris (Fig. 4) on a frequent basis. However, few growers were employing soil or leaf tissue analysis frequently ($\leq$10%), although 60% and 51%, respectively, used these analyses sometimes.

Growers were asked about their perceptions regarding the consequences of using IPM. Most respondents attributed environmental benefits to IPM (75%), and also believed that it could save money (Fig. 5). Sentiment about economic benefits did not seem to be quite as strong. While over 78% of growers agreed that IPM helps to decrease costs of pest management, a large portion of all respondents (30%) agreed only mildly with this statement. A majority of growers (84%) did not feel that using IPM increased the time they devoted to managing their farms. However, many respondents felt IPM carried some risks. For example, many agreed or strongly agreed that IPM use can increase the risk of crop loss (46%) or vine injury (51%).

Many respondents agreed or strongly agreed that pest resistance is an increasing problem for cranberry growers in MA (81%) and many have experienced it first-hand on their own farm (40%). Notably, almost one-fifth of respondents were not sure about experiencing resistance on their own farm. Three-quarters of surveyed growers thought that pest pressures were worse in MA than in other regions of North America, but only 5% thought IPM adoption was more risky in MA than in other production areas. Ninety percent agreed that use of IPM can help resolve the problem of pest resistance (data not shown).

Table 1. *P*-values* and sign[1] of estimates from GENMOD procedure for factors used as predictors and various demographic variables as the outcome.

Factor	IPM adoption	Educational level	Age	Experience	Farm size	Status
Increase in Extension programs	0.018 (–)	0.002 (+)	–	0.085 (+)	–	–
Market price for products	–	–	0.040 (–)	0.038 (–)	–	0.040 (+)
Insurance and promotion	–	–	0.072 (+)	0.004 (+)	–	–
Crop loss and injury	–	–	–	–	0.060 (+)	–
Extension as information source	–	–	–	–	–	–
Non-extension information sources	–	0.091 (–)	–	–	–	–
Late water floods	0.026 (–)	–	–	–	–	–
Reduced rate pesticide use	0.045 (+)	–	–	–	–	0.014 (+)
Fall floods	0.032 (–)	0.028 (–)	–	–	–	–
Soil and tissue tests	0.009 (+)		–	–	0.008 (–)	–
Pruning	0.041 (+)	0.002 (–)	–	0.039 (–)	0.012 (–)	0.007 (+)
Maintenance activities	0.067 (+)	–	–	–	0.012 (–)	–
Low-input insect control	–	–	–	–	0.070 (–)	–
Summer floods	–	–	–	0.079 (+)	0.059 (+)	0.042 (–)
Low-input disease control	0.005 (+)	–	0.028 (+)	–	–	–
Monitoring insects	0.076 (+)	–	–	–	–	–
Low-input weed control	–	–	< 0.001 (+)	–	–	–
Environmental benefits	–	–	–	–	–	–
Risk using IPM	–	–	–	–	–	–
Pest resistance and pressure	0.066 (–)	0.082 (+)	0.002 (+)	0.086 (+)	–	–
Effective insect control	–	–	–	–	–	–
Effective disease and weed control	0.027 (+)	0.016 (–)	–	–	–	–

[1] *IPM adoption*: Negative sign indicates association with less frequent adopters, positive sign with more frequent adopters.
Education level: Negative sign indicates association with more educated growers, positive sign with less educated growers.
Age: Negative sign indicates association with older growers, positive sign with younger growers.
Experience: Negative sign indicates association with more experience, positive sign with less experience.
Farm size: Negative sign indicates association with larger farms, positive sign with smaller farms.
Status: Negative sign indicates association with part-time growers, positive sign with full-time growers.
* Only *P*-values < 0.10 are listed and associated with a sign for the estimate.

Growers who participated in the survey agreed or strongly agreed that many of the existing IPM options were relatively effective in controlling major insect pests, such as cranberry fruitworm and cutworms (Fig. 6). However, fewer agreed or strongly agreed that existing IPM options offered an effective control method for certain problems like dodder and dewberries (only 45% and 18%, respectively).

Survey results: factor analysis and GENMOD results

The 104 question/answer possibilities, based on the factor analysis (see the section 'Statistical analyses'), were condensed to 22 factors (Table 1). Each factor represents an observed pattern of covariance (or correlation) within a group of questions, suggesting that some latent (unobservable) variable is present and influencing the responses to all of the questions represented by that factor. A descriptive identifier was assigned to each factor (column 1 of Table 1). Effort was taken to develop a short phrase that would concisely describe the questions that were grouped together by the factor analysis. For example, the label 'Market price for products' was created to define the factor that was comprised of questions relating to the importance of market prices for reduced risk compounds, market price of biological controls, cost of IPM consultants, and the current commodity price. The factor identifiers were designed to be descriptive enough so the reader could readily associate the significant factors from Table 1 with the descriptions of the results in the text. The *P*-values (indicating the location of significant relationships) and signs (indicating the direction of these relationships) associated with the estimates generated from the GENMOD procedure using the factors as predictors and the six demographic variables are presented in Table 1. Only *P*-values less than 0.10 are associated with a sign for the estimate.

The following discussion is principally organized, for each demographic variable (progressing from left to right), according to the list of factors as ordered in the first column of Table 1. To clarify the trend of the factor listed in the first column, descriptions of survey results and references to one or more specific questions from the survey may be included in the discussion. Specific data are given within the text to provide the reader with a sense of the trends, but the complete data set is not presented herein. The reader should note that Figures 1–6 represent responses from the group as a whole; the following discusses data trends after

the respondents were grouped by demographic variables (e.g., IPM adoption, education level, experience, etc.) A copy of the full factor analyses can be requested from the corresponding author.

Eleven factors were associated with level of IPM adoption (Table 1). NonP overwhelmingly responded that an increase in Extension programs and materials as well as more on-farm demonstrations would encourage them to adopt IPM practices they are not currently using. More than 90% of FreqP and OccP felt that they would be more apt to adopt IPM practices if provided with more IPM-related research and education programs. Educational workshops and availability of informational materials are needed to encourage growers to accept and incorporate IPM practices into routine farm activities.

Late water floods can be used to lower pesticide inputs but the success of this practice is dependent on many variables[36,38]. Due to this perceived risk, many FreqP and OccP never used late water floods (69% and 53%, respectively). Of all the respondents that never used late water floods, 83% were FreqP. Periodic use of the flooding practice was also slightly lower for FreqP than for OccP (26% and 38%, respectively). The use of another flooding practice (fall floods) was similar between FreqP and OccP; 45% and 41% never used fall floods and 38% and 40% occasionally used fall floods, respectively, for insect or weed management. FreqP were more apt to use fall floods rather than late water floods for pest control.

The IPM adoption self-report variable was also associated with grower use of disease monitoring and other important IPM practices for major cranberry disease problems (low-input disease control). OccP were less likely than FreqP to at least occasionally use resistant varieties (36% versus 48%) and more likely to never have used them (64% versus 52%). FreqP more routinely used bloom counts (70% versus 57%) and fruit quality forecasts (52% versus 43%) as part of their disease management program than OccP. Most growers incorporated proper irrigation scheduling into their disease management program (80%).

Grower use of insect monitoring practices considered important components of cranberry IPM programs was also found to be related to their classification as frequent, occasional, or non-IPM users. Frequent use of fruit inspection for cranberry fruitworm was often used by both groups, but was slightly higher for FreqP than OccP (81% versus 68%). Very few FreqP (3%) never used fruit inspection. FreqP were more apt to use pheromone traps (59% versus 24%), out-of-bloom counts (86% versus 61%), and to apply control strategies based on the advice of consultants as part of their routine management program (60% versus 19%) than OccP. Most growers routinely used sweep nets (85%) to monitor for insects. These practices are considered fundamental to basic insect pest management in cranberry.

Differences between the user groups were noted for several other perceptions and practices relating to cranberry pest management. Perceptions of pest resistance and pest pressure varied between FreqP and OccP. OccP were more apt to agree that pest pressures were more severe (86% versus 69%), and that IPM was more risky in MA compared to other growing regions (45% versus 20%) than FreqP, respectively. OccP were also less convinced that IPM could help reduce pest resistance issues than FreqP (31% versus 63%), respectively. FreqP were more apt to frequently use reduced rates of herbicides, insecticides, and fungicides (37%) than OccP (28%). Notably, 12% of FreqP and OccP growers always use the full label rates. FreqP were also more likely to use tissue (65% versus 53%) and soil (73% versus 63%) tests than OccP, at least occasionally. Notably, 42% of OccP and 31% of FreqP never use these crop management practices.

When asked to evaluate the effectiveness of available pest management options, FreqP were more likely to agree or strongly agree that IPM was effective for fruit rot management (70% versus 43%), *Phytophthora* root rot management (63% versus 35%), and dodder control (49% versus 25%) than OccP, respectively (effective disease and weed control). Two-thirds of respondents from each group of practitioners felt that current IPM options were not effective for dewberry control.

Education level was associated with four factors at the 0.05 alpha-level: increase in Extension programs, fall floods, pruning, and effective disease and weed control (Table 1). Growers with at least a high-school education (i.e., more educated) felt they would be inclined to adopt more IPM practices if additional educational materials (62%), research programs (66%) and increased funding for IPM method development (66%) were available. A very large proportion (>83%) of less educated (non-high school graduates) growers agreed or strongly agreed that they would be encouraged to adopt IPM practices through more Extension education and research efforts. Fall floods were not used frequently, but their use was twice as common with more educated growers (16%) than for non-high school graduates (7%). A large proportion of less educated growers (46%) tended to prune frequently to enhance canopy habitat, however, pruning was still used frequently by 39% of more educated growers. Educated growers were more inclined than less educated growers to agree or strongly agree that existing IPM options were effective for fruit rot (66% versus 53%), *Phytophthora* root rot (59% versus 33%) and dodder (45% versus 38%) management, respectively.

Grower age was also associated with four factors at the 5% level: market price, low-input disease and weed control, and pest resistance. Growers under 30 (more so than older growers) felt that the current commodity price was very important with regards to their decisions about pest management. Younger growers also felt the cost of biological control products, reduced risk products, and consulting fees were not important factors. Low-input disease management was used frequently by all age groups, but older growers (50+ years) were more likely than

younger growers to respond that they never used options such as resistant varieties (64% versus 39%), bloom counts for fungicide timing (16% versus 10%) and fruit quality forecasts (11% versus 8%), respectively. In a similar fashion (although the percentages were lower), older growers were slightly more likely than younger growers to never use low-input weed options such as scouting for dodder (9% versus 2%) or spot-treatment control (6% versus 1%), respectively. Growers under the age of 30 were most apt to use raking for dodder control (57%) compared to older growers (27%). Growers over 30 were more inclined than younger growers to agree or strongly agree that pest pressure was more severe in MA than other growing areas. Growers over 40 strongly disagreed that IPM was riskier in MA than in other growing regions.

Growers with 10 or more years experience in cranberry farming were more inclined than less experienced growers (38% versus 22%) to view the cost of reduced risk compounds and biological control products as very important factors in their pest management decisions (market price factor). Though promotion and insurance issues tended to be less influential for experienced growers, almost half of all growers agreed or strongly agreed that insurance and promotion products would encourage them to adopt IPM practices. Less experienced growers were almost twice as likely to never prune (19%) as experienced growers (10%) (maintenance activities).

Growers with large farms (40+ acres) were twice as likely to frequently conduct soil and tissue tests than owners of smaller farms (16% versus 8%, respectively). Similarly, owners of smaller farms (< 40 acres) were almost twice as likely to never conduct monitoring tests compared to larger farms (34% versus 19%, respectively). Small-farm managers were more than twice as likely to never prune (16% versus 6%) and less likely to frequently prune (36% versus 54%, respectively) than managers of large farms. Small farms were more than twice as likely to never receive routine maintenance activities (e.g., leaf removal floods, ditch cleaning, efficient irrigation schedules; 8% versus 2%) and less likely to frequently receive these activities than large farms (64% versus 79%, respectively).

Part-time growers were somewhat more likely to not consider market prices of products as important influences to their pest management decisions than full-time growers (27% versus 20%) and full-time growers were slightly more likely to have these factors frequently affect their IPM decisions than part-time growers (44% versus 37%). Full-time growers tended to use reduced rates of pesticides frequently compared to part-time growers (39% versus 27%). Full-time growers tend to prune frequently (45%) compared to part-time growers (31%).

Discussion

Primarily, the findings of the survey were related to the significant percentage of respondents who appeared to be using multiple IPM component practices, with practices involving monitoring and detection of pests along with judicious use of pesticides being most common. The use of alternative cultural and biological tools such as flooding management practices and biorational pesticides were reportedly used on a frequent basis by only a small number of respondents. In addition, although a very large percentage claimed to use economic thresholds for pest management decision-making, a significant percentage also claimed to rely on other factors such as past experience, first sign of a pest, or a regular schedule. This suggested that many may not be using monitoring and thresholds consistently.

The large percentage of respondents claiming to be frequent IPM users was surprising. As such, developing a profile of the typical IPM user was difficult, and a comparison of frequent, occasional and non-IPM user groups was challenging for some factors. However, limited generalizations can be made about the different groups. For example, the analyses did suggest that self-defined frequent IPM users were more likely to use more IPM component practices as a whole and had more positive perceptions about the efficacious, economic, and environmental implications of IPM adoption.

Frequent IPM users tended to be more likely to possess certain demographic characteristics. More specifically, the results suggested that full-time, highly experienced growers, in charge of larger operations, tended to use more IPM practices on a frequent basis than less experienced growers who worked part-time and managed smaller bogs. Although these findings conflict with previous research[21,40] that has characterized growers with less farming experience as being more likely to adopt IPM or other alternative agricultural practices, other studies have demonstrated that larger farms tend to adopt IPM at a faster rate compared to smaller operations[13,17,41]. The labor-intensive nature of many IPM practices may be serving as a significant constraint for further adoption by part-time growers. Likewise, some IPM practices may be more cost-effective or easier to implement for larger operations, which may have greater income and labor resources to draw upon than comparatively smaller operations. In addition, private consultants may be more apt to solicit large portions of consolidated acreage of a few growers rather than contract with many growers who own only a few acres each.

The finding that respondents with higher levels of education seemed to be using more IPM component practices, such as flooding practices and pruning, also corresponds to previous research[9,20]. This result was not unexpected since many IPM practices require a high degree of knowledge about insect biology or bog ecology.

IPM user groups could not be easily differentiated, however, based solely on their use of selected sources of information on IPM. This was because a large percentage of respondents claimed to rely on the same resources, namely Extension publications, staff and workshops, and

also was likely related to the fact that only a small percentage of respondents claimed not to use IPM at all. The specialized nature of cranberry cultivation and its limited geographic scope most likely has served to limit the number and type of informational sources available to growers.

The strong positive perceptions that most respondents seemed to have about the environmental and economic effects of IPM were also notable. A large number of respondents agreed that IPM can reduce pesticide residues in food and the environment, and can help to preserve beneficial insects. Many also directly cited environmental benefits as an important factor influencing their use of IPM. Significantly, the survey found that a large percentage of respondents had experienced pest resistance firsthand and agreed that it was an increasing problem in MA. Self-defined frequent IPM users were more likely than occasional users to see IPM as a solution to the problem of pest resistance, which suggests that grower concerns about pest resistances may act as an incentive to adoption.

Economic benefits were also cited by many as an important factor influencing their use of IPM. The perception that IPM decreases management costs was held by many. However, respondents appeared to feel less strongly about the economic benefits than potential environmental ones. The perception that IPM can pose measurable economic risk also appeared to act as a barrier to IPM adoption. For example, concerns about the potential for vine injury and crop loss were cited among the most important factors affecting grower pest management decisions. Results implied that the costs of pest control products and services have not acted as significant barriers to adoption.

The high level of grower perception of the efficacy of most current IPM methods for controlling major cranberry pests was notable. Still, many respondents also cited the allocation of more funding resources to IPM method development as a primary factor that could promote them to adopt more IPM practices. This further supported the finding that existing IPM methods for a few pests were viewed as ineffective. Likewise, despite the seemingly overwhelming support for existing cranberry IPM educational materials and programs, the development of more IPM-related research and education programs was cited as a potential major adoption incentive, and growers seemed to have a preference for the on-farm demonstration format.

Another primary incentive to adoption revealed by the survey was the provision of more government cost-share programs. Growers seemed less enthused about other potential sources of economic aid such as crop insurance programs. Many also recognized the important role that future FQPA restrictions may play in the future availability of pest management tools.

IPM adoption continues to be in a fluid state for the cranberry industry. Readers should note that this survey was conducted just prior to a significant economic collapse of the cranberry industry. Growers who responded in this survey were receiving high cash returns for their fruit (often, twice the cost of production) and could afford to use very expensive management options. At the time of this writing, the profit margin for cranberry fruit has become smaller compared to the late 1990s. Future surveys of the cranberry industry could determine if the recent change in economics has influenced growers' perceptions and adoptions of IPM options.

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Testing a complete-diet model for estimating the land resource requirements of food consumption and agricultural carrying capacity: The New York State example

Christian J. Peters[1,*], Jennifer L. Wilkins[2], and Gary W. Fick[3]

[1]515 Bradfield Hall, Department of Crop and Soil Sciences, Cornell University, Ithaca, NY 14853, USA.
[2]305 Martha Van Rensselaer Hall, Division of Nutritional Sciences, Cornell University, Ithaca, NY 14853, USA.
[3]507 Bradfield Hall, Department of Crop and Soil Sciences, Cornell University, Ithaca, NY 14853, USA.
*Corresponding author: cjp20@cornell.edu

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Abstract

Agriculture faces a multitude of challenges in the 21st century, and new tools are needed to help determine how it should respond. Among these challenges is a need to reconcile how human food consumption patterns should change to both improve human nutrition and reduce agriculture's environmental footprint. A complete-diet framework is needed for better understanding how diet influences demand for a fundamental agricultural resource, land. We tested such a model, measuring the impact of fat and meat consumption on the land requirements of food production in New York State (NYS). Analysis was confined to this geographic area to simplify the modeling procedure and to examine the state's ability to reduce environmental impact by supplying food locally. Per capita land resource requirements were calculated with a spreadsheet model for 42 diets ranging from 0 to 381 g d^{-1} (0 to 12 oz d^{-1}) of meat and eggs and 20 to 45% total calories from fat. Many of these diets meet national dietary recommendations. The potential human carrying capacity of the NYS land base was then derived, based on recent estimates of available agricultural land. A nearly fivefold difference (0.18–0.86 ha) in per capita land requirements was observed across the diets. Increasing meat in the diet increased per capita land requirements, while increasing total dietary fat increased the land requirements of low meat diets but reduced the land needed for high meat diets. Higher meat diets used a larger share of the available cropland suited only to pasture and perennial crops. Thus, only a threefold difference was observed for the potential number of people fed from the NYS land base (2.0–6.2 million). In addition, some high-fat vegetarian diets supported fewer people than lower fat diets containing 63–127 g d^{-1} of meat (approximately one- to two-thirds of the national average per capita consumption in the US). These results support the assertion that diet should be considered in its entirety when assessing environmental impact. To more completely understand how diet influences land requirements and potential carrying capacity, this model should be applied across a larger geographic area that encompasses a wider variety of climates and soil resources. To better understand the ability of a local region to supply more of its own food, the model should be moved into a geospatial framework.

Key words: carrying capacity, diet, fat, food consumption, human nutrition, land requirements, local agriculture, meat, model

Introduction

Agriculture faces a collection of potentially irreconcilable challenges in the 21st century: feeding a growing world population that demands a more affluent diet, providing better nutrition for the poor and more balanced nutrition for the rich, adapting to a changing climate, and reducing its impact on the environment. Food consumption and agricultural production are interdependent, and new tools are needed to understand how one influences the other. Peters et al.[1] contended that complete-diet approaches should be used to assess the adequacy of food supplies and

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agricultural production for meeting nutritional goals. In addition, such approaches are needed to understand how human food preferences affect agriculture's environmental footprint. We present and test a framework for modeling how diet influences the requirements for agriculture's most fundamental resource, land, and how those requirements influence the number of people that agriculture can support.

Demand for affluent diets and its impact on agriculture and the environment

Global consumption of meat and other animal products increased throughout the latter half of the 20th century and will probably continue to increase into the foreseeable future. According to Delgado et al.[2], total global meat consumption is projected to grow 65% between 1993 and 2020 (from 184 to 303 million metric tons). This projected surge in global demand has been called the next food revolution[3], and carries a host of consequences both positive and negative. Increases in consumption of livestock products offer the possibility of improved nutrition in developing countries where protein and micronutrient malnutrition are still widespread, and the requisite increases in livestock production offer the possibility of increased incomes for the rural poor[4]. Unfortunately, this surge in consumption may place further strain on the resource base, cause environmental degradation, and concentrate livestock production.

Recent projections of world food supply suggest that agriculture will be able to meet the challenge of increasing consumption of animal products, at least through the first quarter of this century[5–7]. Demand, rather than supply factors, is expected to limit food consumption. However, this is not cause for complacency. It is generally believed that most grazing lands are already harvested at or above capacity and that lands available for conversion to agriculture are of marginal quality. Indeed, Delgado et al.[3] conclude that increased production of meat will require intensification of production. This raises several concerns, three of which are more immediate and others that may manifest over time.

First, competition for water may force agriculture to cede water to domestic and industrial uses and will constrain the expansion of irrigated agriculture unless the water use efficiency of crop production increases substantially[5,8]. Secondly, use of nitrogen fertilizers will be essential for increasing yields[6,9], but nitrogen use efficiency has plummeted and nutrient loading of aquatic ecosystems already causes eutrophication and low-oxygen conditions[10]. Thirdly, Hall et al.[11] fear that policy aimed at reducing the spread of zoonotic diseases may inadvertently marginalize small-scale producers and potentially increase rural poverty.

In addition to these straightforward concerns, agriculture faces multiple limits, the impacts of which are difficult to predict. Cassman[12] argues that declines in soil quality, though difficult to measure, will increasingly constrain production in the 21st century. Heitschmidt et al.[13] and Pimentel and Pimentel[14] suggest that current energy use of livestock agriculture in the US is unsustainable. They offer no timeline over which energy will become a limiting resource; however, Duncan and Youngquist[15] forecast the peak of world oil production in 2007. If accurate, mechanized agriculture will face a serious challenge in this century. Climate change should not prevent agricultural production from keeping pace with food demand for the next 25 years, but Easterling and Apps[16] suggest that beyond a certain threshold, agriculture will be unable to adapt without an increase in food prices. They stress that the value of this threshold can only be estimated with a low degree of confidence, but that the available evidence suggests global temperature increases beyond 2.5°C may reverse the long-term trend of falling food prices. Finally, Tillman et al.[10] claim incentives are needed to protect the ecosystem services inevitably impacted by using land for agriculture. Taken together, these concerns suggest that the global transition to a diet rich in meat and other animal products may not be possible or desirable to maintain in the long run.

Reducing the environmental impact of diet

More than 35 years ago, Reid[17] listed change in dietary patterns among several measures to avert future shortfalls in food production. Though the evidence suggests such 'belt-tightening' will not be necessary for providing an adequate food supply over the next 20 years, the environmental problems caused by current practices already warrant action to mitigate further degradation. Thus, just as production practices and dietary patterns should be considered key to addressing world energy problems, dietary modification should be considered as part of the strategy for reducing the overall environmental consequences of livestock production and agriculture in general. In order for such a strategy to succeed, it is essential to understand the relative resource requirements of different types of diets.

Existing research paints an incomplete and conflicting picture of the resource requirements of diet. Oltjen and Beckett[18] show that dairy systems can produce returns of greater than 100% on the amount of humanly edible energy used to feed livestock, provided that the majority of the feed comes from forages and by-products. Similarly, they show that both dairy and beef can produce net returns on the amount of humanly edible protein used in such systems. Bradford[19] claims that milk produced from irrigated alfalfa can produce more humanly edible energy per acre than using the same land for wheat. In contrast, Reijnders and Soret[20] estimate that cheese requires five times the land area as a lupine-based cheese substitute and meat requires 6–17 times the area of a soy-based meat substitute. Since the methods used in each of these studies are different, it is possible that all estimates are accurate, yet they lead one

to reach very different conclusions about the resource requirements of animal agriculture. To place such estimates in perspective, it is necessary to consider the impact of livestock products in the context of a complete diet and a complete food system.

Within this context, we examine how two components of the human diet, meat and added fats, influence land resource requirements of the human diet and, consequently, carrying capacity. Such analysis is generally done at national or regional scales since most nations ultimately rely upon domestic production for the majority of their food needs. However, this analysis was performed within the geographic confines of a single state, New York, for the following reasons. First, the model is complex, and it was easiest to test the model over a region where uniform assumptions could be made about livestock production practices and crop productivity. Secondly, the data used for input in the model is collected at the state level. Thirdly, it provides insight into the potential contribution of local agriculture to meeting local food needs in a populous region, relevant since environmental concerns about energy use and climate change suggest that food be grown in closer proximity to its point of consumption. It is understood that the area of analysis restricts generalizations of this study to regions with similar climates and land resources to New York. Nonetheless, the research provides a useful framework that could be applied to larger regions.

Methods

A spreadsheet model was used to calculate annual per capita land resource requirements for 42 different dietary patterns varying in terms of total fat and total servings of meat. All diets contained the same number of calories and included foods from each of the major food groups, similar to the approach outlined by Peters et al.[1]. However, not all diets met the recommended number of servings for each of the major food groups in the Food Guide Pyramid. The comparison diets were designed to represent the range of food consumption patterns—from low-fat, lacto-vegetarian to high-fat, meat-rich omnivorous. Estimated per capita land resource requirements were then used to calculate the number of people which could be fed from New York State (NYS)'s agricultural land, based on the quality and quantity of land available. These estimates of carrying capacity are used to examine the interaction between quality of the land resource base and the diet that supports the largest population.

Design of diets

For this study, 42 different diets were constructed for comparison. The parameters underlying the comparison diets used in this analysis are summarized in Table 1[21–23]. The critical components that varied across the diets were the quantity of meat consumed per day and the percent of total energy coming from fat. Seven different quantities of cooked meat and eggs—ranging from 0 to 381 g d^{-1} (0–12 oz d^{-1}) in 63.5 g d^{-1} (2 oz d^{-1}) increments—and six different levels of fat—ranging from 20 to 45% of total calories in 5% increments—were represented in the 42 diets. All seven meat quantities were paired with each of the six fat levels, which generated 42 different diets.

This choice of graduated levels of specific dietary components (meat and fat) allowed for analysis by either two-factor analysis of variance (ANOVA) or multiple linear regression. The range of each component was selected to achieve a thorough representation of the most prevalent consumption practices in the United States today. According to loss-adjusted federal food supply data[24], Americans consumed an average of 163 g (5.8 oz) of meat and eggs per day (in cooked meat equivalents) in 2003 and ate 23% of total calories from 'added fats' (i.e. butter, oil, and other fats that dress other foods or are used in cooking). 'Added fats' account for 56% of the fat available in the food supply[25], which means that 41% of total calories come from fat. Since the national dietary recommendations suggest no more than 30% of calories come from fat, the range represented by the comparison diets included lower amounts.

All diets included representative foods from each food group (grains, vegetables, fruit, dairy, protein-rich foods, oils, and sweeteners) and were equivalent in total caloric value. The composition of each diet was determined through a six-step process. First, 41 food commodities were selected to serve as the constituents of the diet. All commodities produced in NYS were included provided that annual yield data were available from the state agricultural statistics service. Secondly, each food was entered into a spreadsheet along with data on basic nutritional properties (carbohydrate, fat, protein and total energy content) from the Nutrient Database for Standard Reference[26]. Thirdly, the relative preference for individual foods within a food group was derived from the Food Commodity Intake Database[23]. Fourthly, core diets were developed that contained the Food Guide Pyramid (FGP)-recommended servings[22] of grains, vegetables, fruits, low-fat dairy and low-fat protein sources, and contained the level of meat and eggs proscribed for each treatment. Fifthly, fat was added to each diet to bring the total fat to the targeted level. Fat was added first by substituting low-fat dairy and meats with full-fat sources, then by adding plant oils. Finally, diets were adjusted for calories. Diets below the caloric goal were bolstered by adding sweeteners (up to 10% dietary energy) and extra base plant foods (grains, vegetables and fruits). Diets above the caloric goal were trimmed by reducing the quantity of base plant foods. The composition of the diets is outlined in detail in Peters et al.[27].

It is assumed that all food contained in the diets could be grown in NYS. To account for seasonality of produce availability, both 'summer' and 'winter' diets were designed. Only processed or storable fruits and vegetables were used in the winter diets.

Table 1. Summary of diet treatment assumptions.

Parameter	Requirement
Meat	0–381 g d^{-1} (0–12 oz d^{-1}) in 63.5 g d^{-1} (2 oz d^{-1}) increments
Fat	20–45% total calories from fat in 5% increments
Energy[1]	2308 kcal d^{-1}
Geography[2]	Excludes foods that cannot be produced in NYS
Seasonality	Assumes seasonal limitations on fruits and vegetables • Five-month 'summer' diet = available fresh • Seven-month 'winter' diet = available processed or from storage
Nutrition[3]	Meets USDA Food Guide Pyramid recommendations where possible: • Grains, vegetables, and fruit meet or exceed recommendations (unless total kcal limit would be exceeded) • Dairy meets recommendations • Protein meets or exceeds recommendations • Sugar limited to 10% of total kcal • Diets above 30% kcal from fat exceed suggested limit
Food preferences[4]	Relative preferences for individual foods within a food group based on intake data for the Northeast US
Fat sources	Contain a mixture of regular and reduced fat foods • Lower fat diets contain more skim milk and lean meats • Higher fat diets contain more whole milk and meats Include at least one tablespoon plant oil per day

[1] Average energy requirement determined based on population demographics of NYS and recommended Food Guide Pyramid servings by age and gender from Bowman et al.[21].
[2] Includes the following crops (by food group): Grains: corn, oats, rye, and wheat; Vegetables: beets, bell peppers, cabbage, carrots, cauliflower, eggplant, escarole/endive, green peas, lettuce, onions, potatoes, snap beans, spinach, sweet corn, tomatoes, and winter squash; Fruit: apples, apple juice, blueberries, cherries, grapes, grape juice, peaches, pears, and strawberries; Pulses and nuts: black beans, kidney beans, sunflower seeds, and tofu; Meat and eggs: beef, chicken, chicken eggs, and pork; Oils: canola, soy, and sunflower; Sweeteners: beet sugar.
[3] Recommendations of the USDA Food Guide Pyramid are outlined in *Nutrition and Your Health: Dietary Guidelines for Americans*[22].
[4] Intake data for the Northeast US from the Food Commodity Intake Database[23].

Land requirements and carrying capacity estimates

Annual per capita land requirements were calculated based on dietary intake, crop yields and livestock feed requirements (Eqn 1). Average daily dietary intake was used to derive annual food intake for each diet.

$$A_{\text{percap}} = \sum \frac{Q_i \times L_i}{Y_i} + \sum \frac{Q_j \times L_j \times R_{jk}}{Y_{jk}} \qquad (1)$$

For each diet, the per capita area of land required annually (A_{percap}) is the sum of the area required for all plant- and livestock-derived foods. For each plant commodity (i), annual intake (Q) was multiplied by a conversion factor (L) to account for losses incurred in processing, distribution and after purchase by the consumer, as well as inedible portions included in the harvested crop weight. This loss-adjusted weight of food was then divided by the crop yield (Y) to calculate the land requirements per commodity. For each animal product (j), loss-adjusted weight was multiplied by the livestock feed requirements (R) for each ingredient (k) in the ration, and then divided by the associated component crop yield (Y) to derive land requirements. Published estimates of processing yields and post-harvest losses were obtained from US Department of Agriculture (USDA) publications[28–30]. Yield estimates were obtained from both the state[31] and national[32,33] branches of USDA-National Agricultural Statistics Service (NASS). Livestock feed requirements were obtained from the animal science faculty at Cornell University. To account for annual variation in yields, land requirements were calculated using 5 years of crop data: 1999–2003.

Land use data from 1999 to 2003 were used to derive the quantity and quality of available agricultural land in the model. It was assumed that all harvested cropland, cropland pasture and permanent pasture should be considered available for use in the model. For the purposes of estimating carrying capacity, land was divided into three quality categories: cropland useable for all crops, cropland limited to perennial crops and pasture, and land limited to pasture. It was assumed that the current distribution of annual to perennial crops represented a reasonable use of NYS cropland. Based on current land use patterns, a total of 2031 thousand ha were considered available to the model: 712 thousand ha of cropland usable for all crops, 1063 thousand ha of cropland limited to perennial crops and

pasture, and 255 thousand ha limited to permanent pasture[31].

Calculation of carrying capacity of the New York land resource base was performed using the per capita land requirements for each diet in conjunction with estimates of available agricultural land in NYS (Eqn 2). Carrying capacity (C) was determined using a conditional (if/then) equation that determined which category of land was limiting to food production. This was done by comparing the per capita requirements (A) for each type of land to the amounts available (L) in NYS [cropland useable for all crops (a), total cropland (c) pasture land (p) and total agricultural land (t)]. The available land area was then divided by the per capita land requirements for the limiting resource to calculate the potential population fed.

$$C = \text{If}\left\{\left(\frac{A_a}{A_t} > \frac{L_a}{L_t}\right), \left(\frac{L_a}{A_a}\right), \text{if}\left[\left(\frac{A_p}{A_t} < \frac{L_p}{L_t}\right), \left(\frac{L_c}{A_c}\right), \left(\frac{L_t}{A_t}\right)\right]\right\} \quad (2)$$

The estimates of per capita land requirements and potential carrying capacity were analyzed using two-factor ANOVA and multiple linear regression. Two-factor ANOVA was used to determine the percentage of variation that can be explained by the two main factors in the diet: meat and fat. Multiple linear regression was then used to estimate the per unit effect of adding meat or fat to the diet.

Results

Land requirements by category of food

The area of land required to produce different types of food is displayed in Table 2. Total land required per unit of edible energy ranged from 0.6 $m^2\,Mcal^{-1}$ (sugar) to 54.6 $m^2\,Mcal^{-1}$ (lean beef). Several patterns emerge from this comparison. Protein-rich legumes and lipid-rich oilseeds required from 1.6 to 2.2 times the quantity of land per unit edible energy as the carbohydrate-rich grains. Animal products (excluding beef) required 3.3–6.3 times the amount of land as the grains. Beef stood alone in requiring 31 times the land area as the equivalent quantity of grain. However, it was also clear that the majority of the land used by ruminant animals was devoted to perennial crops. The cultivated land requirements for beef were comparable to other meats, while those of milk were the lowest among all protein sources.

Land requirements per capita

A nearly fivefold difference in per capita land requirements was observed between the diets (Fig. 1). Average annual land requirements per person ranged from 0.18 ha (0 g meat, 52 g fat) to 0.86 ha (381 g meat, 52 g fat). In general, per capita land requirements increased with increasing quantities of meat in the diet, while the influence of the quantity of fat varied depending on the quantity of meat consumed. In addition, the proportion of land in perennial crops was greater in higher meat treatments than in lower meat and vegetarian treatments.

Two-factor ANOVA indicated that the quantity of meat in the diet explained the majority of the variability (97.2%) observed between the diets, while the quantity of fat (0.9%) and the interaction term (1.4%) explained only small, though statistically significant, fractions of the total variability (data not shown). However, ANOVA provided no indication of the influence each one unit change in meat or fat had on land requirements. Since both factors are quantitative, it is appropriate to study the nature of the response function using regression analysis[34]. Thus, multiple linear regression was used to model the relationship between the quantity of meat (M), the quantity of fat (F), and the cross-product (C). In this model (hereafter referred to as the MFC model), F was expressed in grams of fat

Table 2. Land requirements per unit edible energy for selected foods and food groups based on crop yields in NYS.

Food	Land requirements		
	Cultivated crops	Perennial crops	Total
	--------$m^2\,Mcal^{-1}$ edible product--------		
Animal products[1]			
Meat and eggs			
Beef, lean cuts	9.2	45.4	54.6
Beef, all cuts	5.3	25.9	31.2
Chicken, lean cuts	14.3	0.0	14.3
Chicken, all cuts	9.0	0.0	9.0
Eggs	6.0	0.0	6.0
Pork, lean cuts	17.9	0.0	17.9
Pork, all cuts	7.3	0.0	7.3
Dairy			
Milk, skim	2.2	6.8	9.0
Milk, whole	1.2	3.9	5.0
Plant products[2]			
Fruits	0.0	2.3	2.3
Grains	1.1	0.0	1.1
Oils	3.2	0.0	3.2
Pulses	2.2	0.0	2.2
Sugar	0.6	0.0	0.6
Vegetables	1.7	0.0	1.7

[1] Assumes the following rations for each class of livestock: (beef) 0.85 ha pasture, 2.4 Mg hay, 1.7 Mg corn, 68 kg soy are required to meet maintenance requirements of cow plus raise calf to market weight; (pork) assumes hog ration is 70% corn, 23% soy, 7% mineral and animals require 3 kg ration per 1 kg of weight gain; (chicken) assumes broiler ration is 60% corn, 35% soy, 5% mineral and animals require 2.1 kg ration per 1 kg weight gain; (eggs) assumes layer ration is 60% corn, 30% soy, 10% mineral and animals are fed 100 g per day for a 55 week period (300 eggs); (dairy) assumes 540 kg grass silage, 300 kg alfalfa silage, 120 kg corn, 90 kg soy, and 50 kg by-product feed are required per 1.0 Mg fluid milk (whole herd average).

[2] Values shown are weighted averages based on the crops included in the model.

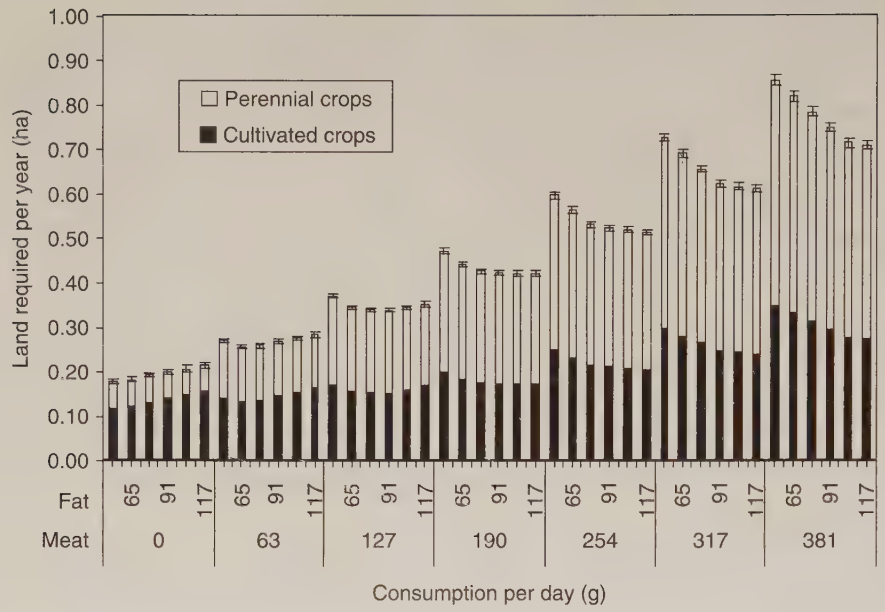

Figure 1. Mean annual per capita land requirements for meeting human food needs according to diets varied in their content of meat and total fat. Assumes all food was grown in NYS (1999–2003 yields). Error bar is standard error of the mean.

rather than percent calories from fat, to allow more ready comparison with *M*. According to the analysis, both *M* and *F* were positively correlated with the annual per capita land requirements, while *C* was negatively correlated (Table 3). In addition, the effect of increasing the *M* in the diet by 1 g was three times greater than that of increasing *F* by 1 g. The total effect of *M* and *F* on the land requirements of diet was mitigated by *C*. The greater range of *M* relative to *F*, combined with the greater impact per gram, explained why meat accounted for nearly all of the variability observed in the ANOVA.

The cross-product *C* is essentially a linear correction for the influence of *F* at a given level of *M*. The regression equation predicted that in low meat diets, land requirements tend to increase with increasing fat, while the reverse is true in high meat diets. This simple correction accounted for much of the variation, but did not explain the mechanism behind the shift. Thus, we decided to decompose *F* into more than one variable.

In theory, fat present in food (e.g. meat fat) or fat inherent to the production of food (e.g. oil expressed from high-protein feed grains) comes at no additional land cost. Therefore, consuming this fat spares land that would otherwise be needed to produce additional calories. Conversely, discarding this fat necessitates that additional land be used. Fat can, therefore, be divided into three classes: fat that is inherent in the production of other foods and is consumed, inherent fat that is discarded, and additional oil crops grown to meet dietary fat goals. Since only the latter two classes should influence land use, an alternative model was developed that predicts land use based on the quantities of meat (*M*), added oils (*A*), and discarded fat (*D*). The resulting model (hereafter referred to as the MAD model) explained slightly more of the variability than the MFC model ($r^2 = 0.99$ versus 0.98), and captured the pattern of variation observed between treatments with different quantities of fat but the same level of meat. According to the regression coefficients (Table 3), *M* caused somewhat greater per unit increases in land requirements than either *A* or *D* (40 and 25%, respectively). However, the range of *M* was much greater than that of *A* or *D*.

Potential carrying capacity of NYS

A threefold difference in potential carrying capacity for NYS was observed among the diets (Fig. 2). The population potentially fed from the NYS land base ranged from 6.08 million persons (0 g meat, 52 g fat) to 2.04 million persons (381 g meat, 52 g fat). In general, the population supported by NYS decreased with increasing fat in the no meat diet, reached a peak then declined in the 63 and 127 g meat diets, and increased with increasing fat in the 190–381 g meat diets. In general, lower meat diets supported more people than higher meat diets. However, the differences between diets with different meat levels decreased as fat increased.

As with land requirements, two-factor ANOVA indicated that meat explained most of the variability (87.2%) observed in carrying capacity across the diets, while fat and the interaction term had small, statistically significant effects (0.5 and 7.3%) (data not shown). Multiple linear regression was used to model the differences in potential carrying capacity and to estimate coefficients. The same two models were used. The MAD model had a slightly better fit to the data than the MFC model ($r^2 = 0.93$ versus 0.92) and better predicted the difference between treatments with the same level of meat consumption. According to the

Table 3. Coefficient values for two multiple linear regression models used to predict the annual per capita land requirements of producing a complete diet from NYS agricultural land and the potential population fed from that land as a function of diet.

			Coefficient values	
Model[1]	**Variable**[2]	**Range of variable**[3]	**Annual land requirements**	**Population**
		(units)	(ha unit^{-1})	(persons unit^{-1})
MFC	Intercept	–	1.10×10^{-1}	6.84×10^{6}
	Meat (g d^{-1})	381	2.18×10^{-3}	-1.56×10^{4}
	Fat (g d^{-1})	65	7.25×10^{-4}	-1.73×10^{4}
	Cross-product (g^2 d^{-2})	44,577	-7.89×10^{-6}	8.88×10^{1}
MAD	Intercept	–	1.66×10^{-1}	5.75×10^{6}
	Meat (g d^{-1})	381	1.25×10^{-3}	-7.95×10^{3}
	Added oils (g d^{-1})	63	8.93×10^{-4}	-1.87×10^{4}
	Discarded fat (g d^{-1})	196	1.00×10^{-3}	-4.60×10^{3}

[1] Model names are acronyms of the variables included in the multiple regression models. See text for complete description of the models.
[2] Variables indicate the quantity of product consumed (avoided) in a given diet. Units are shown in parentheses. See text for complete description of the variables.
[3] Size of the range covered by the diets. Meat ranges from 0 to 381 g d^{-1}, fat from 52 to 117 g d^{-1}, cross-product from 0 to 44,577 g^2 d^{-2}, added oils from 1 to 64 g d^{-1}, and discarded fat from 0 to 196 g d^{-1}.

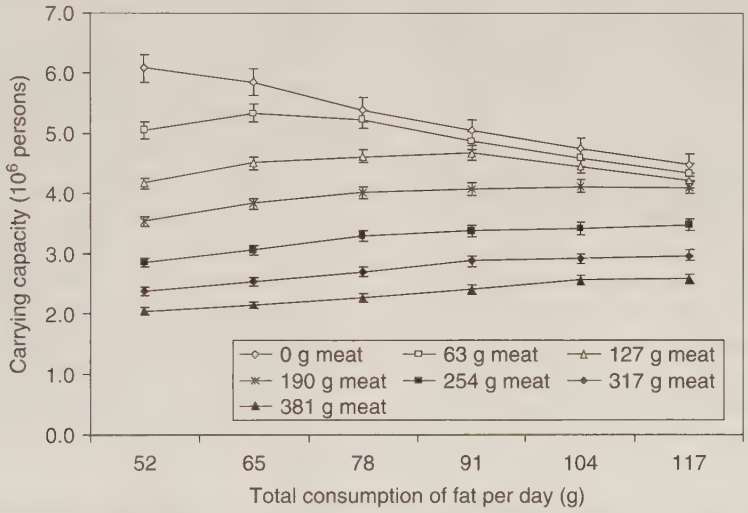

Figure 2. Potential human population supported by the NYS agricultural land base according to 42 diets varied in their content of meat and total fat. Based on 1999–2003 crop yields. Error bar is standard error of the mean.

MFC model, the decrease in potential carrying capacity was slightly greater (12%) per gram of *F* than it was per gram of *M* (Table 3). In addition, the MAD model shows that increases in *A* had a much greater per unit impact on potential population than either *M* or *D* (235 and 407%, respectively). However, the range observed in *M* was much greater than that of either *A* or *D*.

Both models suggested that though vegetarian diets generally support more people, considerable overlap exists with low meat diets. The theoretical carrying capacity of NYS agricultural land was estimated for each level of meat consumption across the entire range of fat (Fig. 3). According to this analysis, a diet containing 63 g (2 oz) of meat and 71 g (27%) fat would support the same population as a vegetarian diet containing 80 g (31%) fat. Similarly, a diet containing 127 g (4 oz) meat and 90 g (34%) fat could support a population equal to that of a vegetarian diet with 107 g (41%) fat. No overlap with the vegetarian diet occurred for the diet containing 190 g meat.

Discussion and Conclusions

The land required to produce a calorie of food in NYS demonstrates that a hierarchy exists in the resource requirements of producing food. If a continuum were to be drawn, meat would lie at the land intensive end of the spectrum followed by eggs, dairy, fruits, oilseeds, vegetables, beans, and finally grains. However, the results also indicate that ruminant meat and milk requires less land devoted to annual crop production relative to other meats

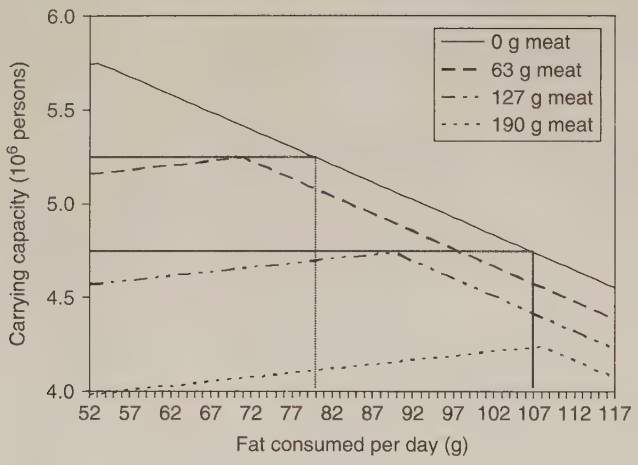

Figure 3. Carrying capacity of NYS agricultural land as a function of diet according to the coefficient values of the MAD (meat, added fat, discarded fat) multiple linear regression model. Lines parallel to the axes indicate where some lower-fat omnivore diets feed as many, or more, people than higher-fat vegetarian diets.

and beans. Thus, we conclude that the inclusion of beef and milk in the diet can increase the number of people fed from the land base relative to a vegan diet, up to the point that land limited to pasture and perennial forages has been fully utilized.

Observed per capita land requirements for each diet make sense in light of the individual food or food group land requirements; however, the complete diet calculations highlight an important interaction. Overall, meat is the primary driver of increasing land use in the range of diets observed. The fat content of the diet only influences the quantity of land required when it necessitates that additional oil crops be grown to meet the demand for fat or that fat be avoided in favor of leaner meat, low-fat milk and extra plant carbohydrates. It is important to note that this 'avoided' fat is unlikely to be discarded. Rather, such surplus commodities are simply transferred to another population. Thus, the 'discarding' of fat may represent a cost in terms of poor nutrition rather than increased land use.

Calculation of the potential carrying capacity of NYS also demonstrates the interaction between resource base and diet. The range in per capita total land requirements suggested that the least land intensive diet would feed five times the number of people as the most land intensive diet. However, the population estimates show just a threefold difference in population. This is explained by the fact that higher meat diets use a greater proportion of the available perennial forage and pasture land. In addition, the higher populations supported by lower fat, non-vegetarian diets relative to higher fat, vegetarian diets support the claims by animal scientists[18,19] that the inclusion of animal products in the diet can increase the amount of humanly edible calories available in the food supply. Indeed, more substantial differences may have been observed had a vegan diet been included among the diet scenarios. Nonetheless, it is critical to note that the area of overlap observed occurs between 63 g (2 oz) and 127 g (4 oz) of meat, far below the 163 g daily consumption of the average American.

The implications of this analysis with regard to the agricultural carrying capacity of NYS are clear. The New York land base is too small to support the resident population. While it could feed a significant portion of the population (21%, based on the 2000 Census[35] and assuming a 190 g meat, 30% fat diet), it will remain a net food importer. Furthermore, in regions with similar climate and land resources, such as the Great Lakes area of the US and Canada, it appears that while meat increases land requirements, diets including meat can feed more people than some higher fat vegetarian diets. In order to determine if these patterns hold true for agriculture in general, the model would need to be applied across a wider range of environments and animal production systems. Per capita land requirements and potential carrying capacity should not be the final arbiter on what is considered the optimal diet, but an accurate understanding of how diet influences land use is essential to making wise decisions on policy that influences food security, nutrition and environmental degradation.

Fraser[36] argued that research and analysis are needed to correct the overly simplistic and contradictory perceptions that pervade the 'debate' on animal agriculture. Our analysis shows that kernels of truth exist in both the claim that livestock production decreases the food supply and the claim that livestock production increases it. On balance, meat increases the land requirements of diet more so than fat. However, diets which include modest levels of meat and fat consumption can feed slightly greater numbers of people than vegetarian diets that provide more generous quantities of fat. Future research on the resource requirements of diet should not consider the impact of individual foods in isolation, but in the context of a complete diet and a complete food system.

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Book Review

The End of Poverty: Economic Possibilities for Our Time. By Jeffrey D. Sachs. 2006. Penguin Books, New York, NY. xviii+397 pp. US$16.00, ISBN: 0-14-303658-0, paperback.

In what is likely to be a highly controversial book in global economic circles, macro-economist Jeffrey Sachs provides a critical analysis of current failed development aid policies of the World Bank and the International Monetary Fund in the eastern block and the Third World. Based on extensive travel, consulting with governments, and practical experience with both successes and failures, the author provides convincing evidence that a major shift in assistance policy is needed to alleviate poverty in our time. Yet contrary to many who see the challenges in Asia and especially Africa as impossible to solve, Sachs provides an impressive agenda of practical solutions that can help the global community meet the Millennial Goals of reducing poverty.

Professor Sachs provides enough historical perspective on poverty in general as well as background on the specific country case studies to convince the reader of the soundness of his scholarship. Yet he is no armchair academic. The author knows first-hand the challenges that face the poor from his visits to villages and families in impoverished areas of India, Malawi and Ethiopia. At the same time, he has counseled ministers of state and other national leaders about their macro-economic problems and has challenged them to seek bold new solutions that will break the chains of poverty and help people and societies reach the first rung on the ladder to development. His comprehensive economic research, acquired grasp of agricultural and environmental issues, and exhaustive travel provide credibility to the recommendations, and make this a compelling book for anyone interested in creative approaches to development and solving poverty.

The importance of history is chronicled through the past two formative centuries, during which a large disparity of wealth and power developed. Before this time, people were generally and equally poor in all parts of the world, except for a small elite. Dr Sachs provides analysis of how the highly developed cultures of China and India fell victim to their own parochial decisions, lack of internal unity, and limited foresight while the emerging industrial economies of western Europe rapidly gained control of the sea and global trade. Colonies were established that focused on extraction rather than education and local development, and the legacy lives on until today in great disparities in wealth and access to resources. His first three chapters remind the reader of another sweeping analysis of global development, *Guns, Germs, and Steel* by Jared Diamond (Norton, 1997), an equally over-simplified rendition of history, to be sure, but a provoking treatise that stimulates thinking and further reading.

The book expands the theme of 'clinical economics' or careful analysis in a series of chapters dedicated to specific national situations in Bolivia, Poland, Russia, China, India and, lastly, several countries in sub-Saharan Africa, presented roughly in the order of the author's own involvement. These are riveting exposés of the unique challenges faced by societies with different political histories, natural resource endowments and potential access to global trade. Dr Sachs' personal involvement and his descriptions of the leaders with whom he has counseled make fascinating reading, especially since most of this has happened in the past several decades and most readers will recognize the names and events. Telling the stories in first person provides a readable and interesting text, although the author's ego can be a distraction as one grinds through page after page of his personal exploits and influence on the course of economic development. Further, his great discovery that different countries and situations will require unique solutions may be a revelation to development economists, but should be greeted with a yawn by anyone with knowledge of ecology, diversity and the importance of place and context.

Where the book excels is in the last eight chapters, where a clear path to development is laid out. Modestly named and described by Sachs as his 'Big Plan' for development, the solutions rightly focus on integrated activities on multiple fronts in the battle against poverty. He claims that piecemeal approaches that look at single factors in a national economy are unlikely to have major impacts on development, while he does concede that some interventions such as oral rehydration therapy and infusion of chemical fertilizers, for example, can help people toward better health and increased agricultural production. Again, this may be news to economists, but agronomists and ecologists are well aware that all things are connected and that tweaking one part of the system, whether through introduction of a new wheat variety or establishing export subsidies, alone is unlikely to make much change. But these shortcomings should not detract the reader from the central message of *The End of Poverty*.

There is ample evidence provided by Dr Sachs for hope rather than total despair in moving toward solutions to poverty. Although many of the economic details and arguments will be difficult for the general reader, he does provide some simplified examples at the family and the village levels that demonstrate clearly how a modest investment from outside can make a substantial difference in incomes and human well being. He outlines in very accessible language what needs to be done, and compares the required financing on a global scale to what is now invested in military equipment and adventurism that could be put to much better use in improving the human condition. The author is unforgiving in his assessment of

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the current US administration's fixation with national security and singular military solutions to stabilize the world so that a global economy can be assured.

This introduces another major shortcoming in the Big Plan. Although framed in a reformist context compared to simplistic efforts at foreign development assistance in the past, there is an over-reliance on neoclassical economics and development of free trade on a global scale to guarantee progress for everyone. The author rightly describes the great disparities in wealth that have evolved over the past several decades as a result of uncontrolled capitalism and the rise of multinational corporations. Yet there is little attention to creative alternatives at the family, landscape and community level, such as local food systems, self-reliant agricultural production systems and other innovations that are emerging with current research in agroecology and organic farming. The concerned reader would be well advised to explore the opinions of another economist, Dr John Ikerd, in *Sustainable Capitalism: A Matter of Common Sense* (Kumarian Press, 2005) to discover truly creative alternatives.

For Dr Sachs and other economists, there is no other economy, for example based on water, energy, carbon balance or metrics of global climate change. They are realists, of course, as our societies are not well enough educated to understand or accept the real constraints in the long term: declining supplies of fossil fuels and fresh water, loss of farmland to development, unrestrained competition within and among countries, among others. We also lack the tools and the will to develop and engage in any other long-term measure of sustainability.

This said, Dr Sachs' provocative book *The End of Poverty* is an essential read for those seriously concerned about international development and the importance of the role of rich countries in this process. It is not an oversimplification to say that we are all connected, and that our long-term survival depends on the fortunes of those in the poorest countries as well as solving the inequities in income in developed countries. Stabilizing population, working within the Earth's carrying capacity, recognition that biodiversity is essential for our own survival, and accepting that we are subject to the same natural laws as other species must be coupled with a rational approach to economics and capitalism for us to truly discover an end to poverty and global stability. This book furthers the arguments toward broad and sweeping reforms of development aid, while it raises questions about how this should happen at the community level.

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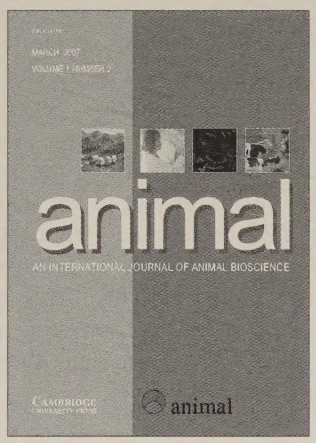

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